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A B S T R A C T

Recent research suggests that eye contact can lead to enhanced self-awareness. A related phe- nomenon, the sense of agency deals with the notion of the self as the origin of our actions. Possible links between eye contact and agency have been so far neglected. Here, we investigated whether an implicit sense of agency could be modulated by eye gaze. We asked participants to respond (button press) to a face stimulus: looking or not at the participant (experiment 1); or displaying distinct eye gaze before or after a mask (experiment 2). After each trial, participants estimated the time between their key press and the ensuing effects. We found enhanced inten- tional binding for conditions that involved direct compared to averted gaze. This study supports the idea that eye contact is an important cue that affects complex cognitive processes and sug- gests that modulating self-processing can impact the sense of agency.

Keywords: Eye contact, Self-referential processing, Agency, Intentional binding

1. Introduction

Eye contact is a powerful social cue and is fundamental in the development of social skills in humans (Emery, 2000). Eye contact plays an important role in social behavior; it is the customary prelude for social interaction (George & Conty, 2008), it is used for regulating turn taking in conversations, in expressing certain attitudes such as liking or loving, and in exercising social control (Kleinke, 1986). The underlying mechanisms associated with the effects of eye gaze are now being extensively studied in psychology and neuroscience (Carlin & Calder, 2013; Senju & Hasegawa, 2005). Some theoretical developments suggest that important effects of perceiving eye contact derive from cognitive processes associated with the processing of the self. Eye contact is said to induce "attention toward the self" and to trigger a self-centered frame of reference for cognitive processing (Conty, George, & Hietanen, 2016). The emergent literature on this topic gives support to these ideas. For instance, eye contact displays enhanced self-awareness, making participants better at reporting their own emotional responses (Baltazar et al., 2014). Given the nature of these effects, one could venture that cognitive processes that depend on perception of the self could be modulated by eye contact. The sense of agency (SoA), i.e. the experience that we are in control of our actions and their effects (Gallagher, 2000; Haggard & Tsakiris, 2009) is a cognitive process closely related to the processing of the self. SoA involves performing actions, monitoring their consequences, and attributing (or not) these consequences to oneself (David et al., 2008). There are now several studies investigating the factors that modulate SoA. It has been shown that SoA is modulated by basic sensorimotor processes (e.g. Chambon & Haggard, 2012) as well as high-level inferential factors associated with intentions and beliefs (see Synofzik, Vosgerau, & Voss, 2013 for an integrative view). Another aspect of SoA is its affective and social dimension (Gentsch & Synofzik, 2014). It has been shown for instance that eliciting sadness by invoking social exclusion memories (Malik & Obhi, 2019), evoking fear (Christensen, Di Costa, Beck, & Haggard, 2019) or anger (Christensen et al., 2019) in participants, reduces intentional binding, an implicit form of the SoA. Other aspects related to emotional processing also change SoA, for instance valence and arousal of stimuli. Yoshie and Haggard (2013) showed that negatively-valenced outcomes lead to decreased temporal binding, while increased levels of arousal have been shown to increase intentional binding (Wen, Yamashita, & Asama, 2015). In addition, it has been shown that social interaction can shape the SoA. Obhi and Hall (2011) have shown that a person involved in a joint action with another subject show intentional binding over its own actions (and that of the other subject) and joint effects. Social cues, however, have been less investigated. Recently, a study investigated the effects of eliciting joint attention on SoA. This study manipulated a face display so that it looked it was engaged in joint attention with the participant or not (Stephenson, Edwards, Howard, & Bayliss, 2018). Participants were asked to reproduce the time between an object appearance (which triggered the participant's saccades) and the gaze onset of the face (the consequence of the participant's saccades). This study showed that making saccades which were followed by another person elicited a reduced intentional binding effect, and thus increased SoA on these outcomes. This effect was absent in experiments with passive gaze changes or gaze changes elicited in a non-social context (Stephenson et al., 2018). Here, unlike focusing on eye movements we were interested in understanding the influence of eye contact on SoA. Indeed, a crucial aspect of SoA is self-referential processing, and as mentioned above, current evidence indicates that eye contact elicits an enhanced processing of the self. Given this obvious relationship between self-related processes and SoA, it is remarkable that no study has been performed to investigate whether changes in self-referential processing affects SoA. In the current study we investigated whether enhanced self-processing, induced by eye contact, could modulates SoA. We adopted an intentional binding approach as a measure of SoA. The intentional binding effect is an implicit measure of agency, which denotes the subjective compression of the temporal interval between actions and their ensuing effects (Haggard, Clark, & Kalogeras, 2002). This effect can be measured by asking participants to report the perceived duration of intervals between an action and its ensuing effect (Cravo, Claessens, & Baldo, 2009; Engbert et al., 2008; Kühn, Brass, & Haggard, 2013; Vastano, Pozzo, & Brass, 2017). The advantage of implicit measures versus explicit measures of agency (self-report of action-effect control) is that implicit measures do not rely on conscious reflection prone to subjective beliefs, contextual cues and differences in personality (Synofzik et al., 2013).

In a first experiment, we asked participants to respond to the sight of face stimuli. The response of participants triggered a gaze shift in the face stimulus with gaze transitions going either from averted to direct gaze, or from direct to averted gaze. The gaze shift occurred after a random interval following participants' response. At the end of each trial we asked participants to estimate the time interval between their action and the ensuing gaze change (the action effect). We hypothesized that a situation where eye contact is induced (a transition from averted to direct gaze) would enhance self-processing and will produce a larger intentional binding effect (and thus enhanced SoA) relative to the condition where the action induces averted gaze. Next, we performed a second experiment to assess this effect for stimuli that displayed a single static gaze direction (either direct or averted gaze). In this second experiment, we masked the eyes of the face before or after the participants' action. Participants observed faces with visible eyes (with direct or averted gaze) that turned into faces with masked eyes (as an effect of their action); or they observed faces with masked eyes that turned into faces with visible eyes (with direct or averted gaze). Following our previous findings, we hypothesized that only those trials where eyes are directed to the participant would increase intentional binding, independently of whether direct gaze was presented before or after the participants' action. Finally, in order to control confounds related to changes in time estimations due to eye contact we performed a third experiment. In this experiment participants were asked to estimate time between sensory events (without performing actions). We do not find evidence for the idea that gaze direction improve the precision of time estimations.

2. Material and methods

2.1. Experiment 1

2.1.1. Participants

Thirty healthy volunteers (23 females, age: 18–21 years, SD: 0.9 years) were enrolled for the study. All participants were right-handed. All testing procedures were approved by the local ethical committee of Ghent University. All participants gave written informed consent and received academic credits for their participation.

2.1.2. Stimuli and procedure

Subjects were seated at a distance of ~60 cm from the computer monitor (refresh rate: 60 Hz, dimensions: 53 × 30 cm, resolution: 1920 × 1080). Experimental stimuli consisted of images (680 × 808 pixels) of 18 neutral human faces (9 female, 9 male) displaying either direct or averted eye gaze (toward left or right). We used the Radboud Faces Database (RaFD; Langner et al., 2010). Participants were presented with a fixation cross between 1500 and 3000 ms, followed by a face to which they had to respond with a key press at the time they chose (provided the experiment was completed in 30 min). The key press produced a gaze change after a variable interval (300, 500 or 700 ms). Gaze transitions went either from averted to direct gaze (Averted-Direct) or from direct to averted gaze (Direct-Averted). The face remained on screen for 500 ms after the gaze change and then it was followed by a Visual Analogue Scale (VAS; Fig. 1). Participants were asked to estimate the time interval between their action (key press) and the ensuing gaze shift, by positioning the mouse pointer along the VAS from 100 ms to 900 ms (the scale displayed a marker every 100 ms just for visualization). They had a maximum of 5000 ms to give their answer. Finally, after a variable inter-trial interval ranging from 1000 to 2000 ms, the next trial started. Participants were told that the interval between their action and the gaze shift was always random between 100 ms and 900 ms. The experiment consisted of one block of 216 randomized trials: 108 trials for Averted-Direct transitions (54 trials from leftward to direct gaze, and 54 trials from rightward to direct gaze) and 108 trials for Direct-Averted transitions (54 trials from direct to leftward gaze, and 54 trials from direct to rightward gaze). The 54 trials of each transition were composed of 18 trials for each action-effect time interval (300, 500, and 700 ms). Before starting the actual experiment, participants were trained to discriminate between 100 and 900 ms (the endpoints of the VAS used in the interval-time estimation task). They observed a visual stimulus (a dot) that changed color after their action with an interval of 100 or 900 ms, and they were asked to evaluate whether the time elapsed between the two color changes was either 100 or 900 ms. At the end of their judgment, they received a feedback (correct or incorrect response). Thirty randomized trials (15 for each interval) were presented with a variable inter-trial interval between 1000 and 2000 ms. After this initial training, participants get familiarized with the main experiment (16 trials). The tasks were implemented in E-prime 2.0 Professional software (Psychology Software Tools, Pittsburgh, PA).

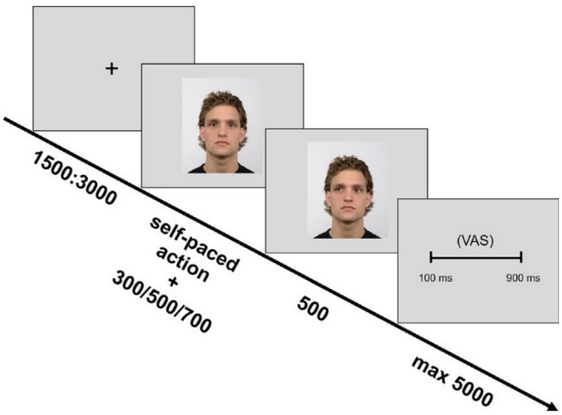

Fig. 1. The sequence of events for the experiment 1. Subjects responded with a button press to the sight of the face. Upon the participant's response and a variable interval there was an eye gaze change in the face. Following the eye gaze change, a Visual Analogue Scale was displayed.

2.1.3. Data analysis

We computed the time-judgment errors as the difference between the estimated intervals and the actual intervals. For the analyses, we first ran a paired t-test on reaction times (RTs) with Gaze transition (2 levels: Averted-Direct, Direct-Averted) as factor to investigate whether there was a difference in reaction time when seeing the averted gaze or the eye contact first. Most importantly, we performed a repeated measures analysis of variance (ANOVA) on the time-judgment errors with Gaze transition (2 levels: Averted-Direct, Direct-Averted) and Interval (3 levels: 300, 500, and 700 ms) as within-subject factors. We tested for sphericity violations and Greenhouse–Geisser corrections were applied when necessary; we report corrected degrees of freedom in these cases. Significant effects found in the ANOVA were followed by Newman-Keuls corrected post hoc tests. Alpha level was fixed at 0.05 for all statistical tests.

2.1.4. Results

2.1.4.1. Reaction times. The paired t-test on RTs revealed no difference for Gaze transition (means: 608 and 607 ms for Averted-Direct and Direct-Averted transitions, respectively, $t(29) = -0.63$, $p = 0.52$) indicating that participants responded equally fast to the face with initial averted gaze as to the face with initial direct eye.

2.1.4.2. Time-judgement errors. The ANOVA on time-judgment errors revealed a main effect of Interval ($F(1.13, 32.95) = 40.31$; $p < 0.001$; partial eta-squared, $\eta^2 p = 0.58$) with larger time-judgement errors for longer intervals and an interaction between Gaze transition and Interval ($F(2,58) = 4.18$; $p = 0.019$; $\eta^2 p = 0.12$). Post-hoc comparisons showed that Averted-Direct transitions led to significantly greater time estimation errors (mean ± SD: −21 ms ± 67 ms) than Direct-Averted transitions (−6 ms ± 70 ms; $p = 0.003$; Fig. 2) for the interval 300 ms only. No other comparison was statistically significant ($p > 0.1$).

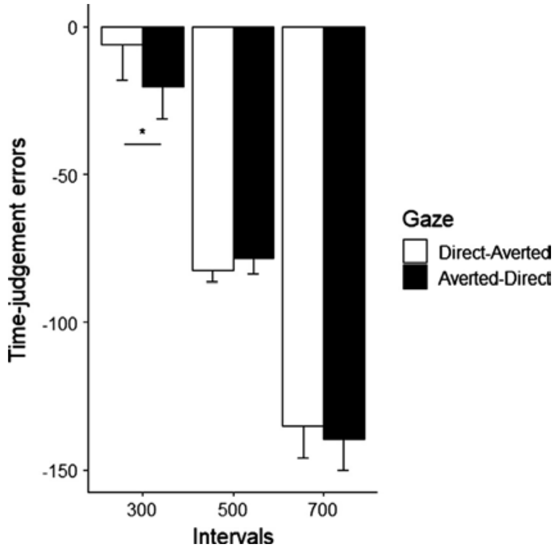

Fig. 2. Time-judgements errors in the experiment 1 as a function of Gaze transitions (Direct-Averted/Averted-Direct) and Intervals (300/500/700). Error bars represent standard errors of the mean.

2.1.5. Discussion

In the first experiment, we observed a larger intentional binding effect indicated by larger negative time-judgement error when participants perform key presses that produce a display of direct gaze as compared to those that produced an averted gaze. This effect was restricted to the short time interval. This result suggests that eye contact has an impact on SoA. However, the specific interpretation of this result is difficult because the first experiment confounds a number of factors. It is not clear whether the influence on intentional binding is caused by eye contact in the first frame (before the action) or the second frame or by the transition from the first to the second image. In addition, it remains an open question whether inducing the direct gaze alone, or in conjunction with averted gaze in this dynamic transition is crucial for the effect to occur. Therefore, we carried out a second experiment in which we controlled for these confounding factors by displaying the face with averted or direct gaze either in the beginning of the trial or as an effect of the key press, at the end. When the eye gaze was presented at the beginning of the trial, the eyes were masked at the end. When the eye gaze was presented at the end, the eyes were masked in the beginning of the trial.

2.2. Experiment 2

2.2.1. Participants

Twenty-seven healthy volunteers (25 females, 18–22 years, SD: 0.9 years) who did not participate in the first experiment were enrolled for the study. All participants were right-handed. All testing procedures were approved by the local ethical committee of Ghent University. All participants gave written informed consent and received academic credits for their participation.

2.2.2. Stimuli and procedure

This experiment was conducted under similar conditions as Experiment 1. Experimental stimuli consisted of 10 neutral human faces (5 female, 5 male) displaying either direct gaze, averted gaze (toward the left or the right), or masked eyes in the form of black sunglasses. In this experiment, gaze transitions could go from masked to visible eyes or from visible to masked eyes (Fig. 3). The visible eyes displayed Direct or Averted gaze, and the display of the visible eyes could occur Before or After the participant's action (Visibility order). The experiment consisted of one block of 192 randomized trials: 96 trials started with visible eyes and ended with masked eyes, and 96 trials started with masked eyes and ended with visible eyes. From the 96 trials for each eye visibility order condition, 48 trials comprised direct gaze, and 48 trials comprised averted gaze (24 averted gaze to the left; 24 averted gaze to the right). Finally, from the 48 trials for each gaze and visibility order condition, there were 16 trials for each action-effect time Interval (300, 500, and 700 ms). Before starting the actual experiment, participants performed a similar short training and a task familiarization as in Experiment 1.

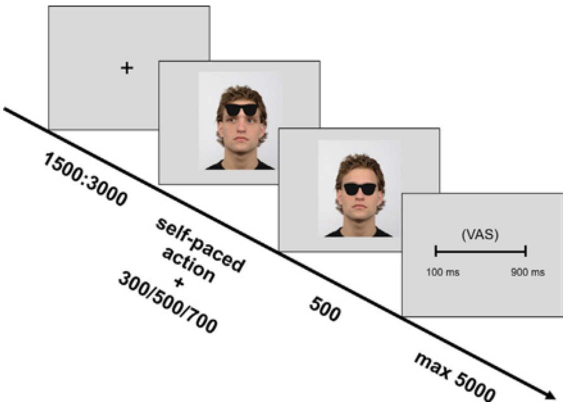

Fig. 3. The sequence of events for the experiment 2. Subjects responded with a button press to the sight of the face. Upon the participant's response and a variable interval there was a change in the face (the presence or absence of the black sunglasses). Following the eye gaze change, a Visual Analogue Scale was displayed.

2.2.3. Data analysis

We computed the time-judgment errors as in Experiment 1. We performed a repeated-measures ANOVA on RTs with Gaze condition (2 levels: Averted, Direct) and Visibility order condition (2 levels: Before, After) as within-subject factors. We performed a repeated-measures ANOVA on the time-judgment errors, with Gaze condition (2 levels: Averted, Direct), Visibility order (2 levels: Before, After) and Interval (3 levels: 300, 500, and 700 ms) as within-subject factors. We tested for sphericity violations and Greenhouse–Geisser correction were applied when necessary; we report corrected degrees of freedom in these cases. Significant effects found in the ANOVA were followed by Newman-Keuls corrected post hoc tests. Alpha level was fixed at 0.05 for all statistical tests.

2.2.4. Results

2.2.4.1. Reaction times. The ANOVA on RTs revealed no main effect nor interaction (all $p > 0.1$) indicating that as in Experiment 1, reaction times were not influenced by the gaze manipulation in the first frame.

2.2.4.2. Time-judgement errors. The ANOVA on time-judgment errors revealed a main effect of Interval ($F(1.14, 29.84) = 53.4$; $p < 0.001$; $\eta^2p = 0.67$) with larger time-judgement errors for longer intervals and an interaction between Gaze and Interval ($F(2,52) = 8.15$; $p < 0.001$; $\eta^2p = 0.24$). Since the Visibility order did not show any main effect or interaction, post-hoc tests were performed collapsing across this factor. Post-hoc comparisons showed that Direct gaze led to significantly greater time estimation errors (mean ± SD: −113 ± 93 ms) than Averted gaze (−90 ms ± 93 ms; $p < 0.001$; Fig. 4) for the interval 500 ms only. No other comparison was statistically significant ($p > 0.1$; Fig. 5).

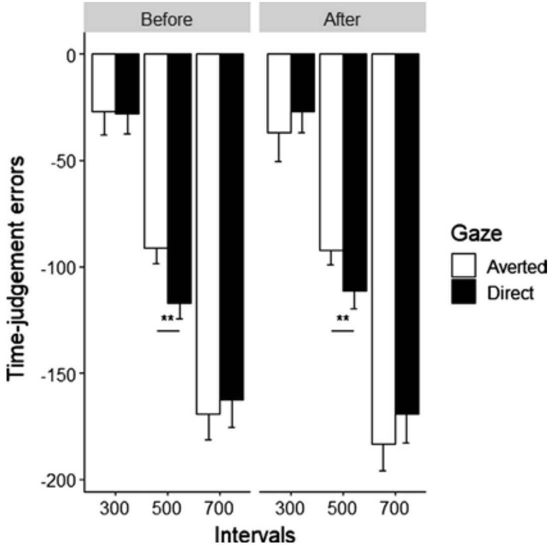

Fig. 4. Time-judgements errors in the experiment 2 as a function of Gaze (Averted/Direct), Intervals (300/500/700) and Visibility order (Before/After). Error bars represent standard errors of the mean.

2.2.5. Discussion

The second experiment investigated if the effect of eye gaze could be observed when gaze stimuli were displayed in the beginning or at the end of the trial only. We observed that conditions involving a direct gaze (regardless of whether it was presented before or after the action) produced enhanced intentional binding, with greater underestimation of time interval between the key press action and its effect for Direct relative to Averted gaze. This effect, however, was restricted to the 500 ms condition. Thus, eye contact elicits enhanced intentional binding irrespective of whether the eye contact precedes or follows the key press, but in a restricted time frame. Finally, we conducted an additional experiment to control confounds related to changes in time estimations due to eye contact. In this experiment participants were asked to estimate time between sensory events (without performing actions).

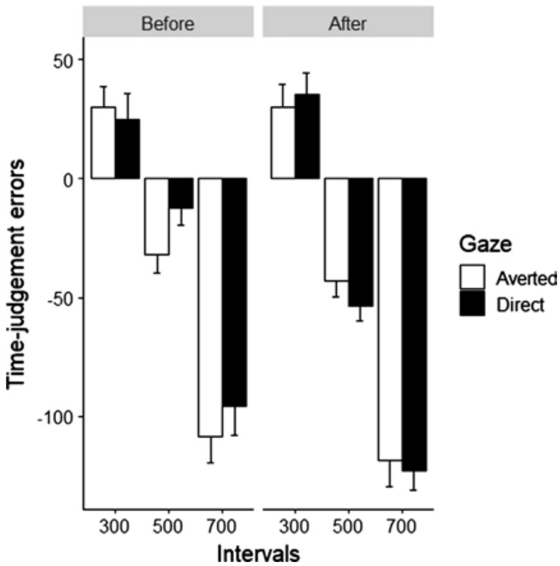

Fig. 5. Time-judgements errors in the experiment 3 as a function of Gaze (Averted/Direct), Intervals (300/500/700) and Visibility order (Before/After). Error bars represent standard errors of the mean.

2.3. Experiment 3

2.3.1. Participants

Thirty healthy volunteers (19 females, age: 18–25 years, SD: 1.47 years) were enrolled for the study. All participants were right-handed. All testing procedures were approved by the ethical committee of the Faculty of Psychology at the University of Talca. All participants gave written informed consent and received monetary compensation for their participation.

2.3.2. Stimuli and procedure

The experiment was conducted under similar conditions as experiment 2 using the same visual stimuli (to visualize a trial see Fig. 1). However, in this experiment the participants do not responded with a button press to the sight of the face. Instead, they only witnessed the transitions between visual displays (the same previous time intervals of 300, 500 and 700 ms were used). As in the previous experiment gaze transitions could go from masked to visible eyes or from visible to masked eyes. The visible eyes displayed Direct or Averted gaze, and the display of the visible eyes could occur Before or After the visual change. Upon these events participants were asked to estimate, in a Visual Analogue Scale, the changes in the face (the presence or absence of the black sunglasses). The experiment consisted of the same number of trials as in the previous experiment and the participants also performed a short training and a task familiarization.

2.3.3. Data analysis

We computed the time-judgment errors as in Experiment 2. We performed a repeated-measures ANOVA on the time-judgment errors, with Gaze condition (2 levels: Averted, Direct), Visibility order (2 levels: Before, After) and Interval (3 levels: 300, 500, and 700 ms) as within-subject factors. We tested for sphericity violations and Greenhouse–Geisser corrections were applied when necessary; we report corrected degrees of freedom in these cases. Significant effects found in the ANOVA were followed by Newman-Keuls corrected post hoc tests. Alpha level was fixed at 0.05 for all statistical tests.

2.3.4. Results

2.3.4.1. Time-judgement errors. The ANOVA on time-judgment errors revealed a main effect of Interval ($F(1.26, 36.62) = 92.1$; $p < 0.001$; $\eta^2p = 0.76$) and a main effect of Visibility order ($F(1, 29) = 4.24$; $p = 0.048$; $\eta^2p = 0.12$). There was also an interaction between Interval and Visibility order ($F(1.66,48.3) = 6.9$; $p = 0.003$; $\eta^2p = 0.19$). Post-hoc tests revealed that this interaction reflect a reduction of time-judgement errors when gaze was displayed before (as compared to after) the visual transition, only for the 500 ms Interval ($t(65.2) = 3.2$, $p = 0.026$). We do not observe any main effect or interaction of gaze ($p > 0.1$).

2.3.5. Discussion

In a third experiment we investigated whether we could find effects of eye gaze direction on a time estimation task involving only sensory events. We observed a main effect of interval with larger time-judgement errors for longer intervals. We also observed that time-judgement errors were overall reduced compared to the previous experiments where participants performed actions. We found that the presence of eyes after relative to before the visual change induced increased time-judgement errors. This effect might be attributed to expectation of a meaningful event such as the imminent presence of eye gaze (regardless of gaze direction). Importantly, we do not observe any main effect or interaction with gaze. This experiment suggest that our previous findings involving modulations of intentional binding by gaze direction cannot be explained only by changes in time estimation. This experiment also suggest that the effects of gaze in intentional binding occur under the presence of voluntary actions only.

3. General discussion

In the present study, we investigated whether eye contact can impact an implicit measure of SoA, namely intentional binding. We observe that eye contact elicits larger intentional binding when the action of participants induced a shift from averted to direct gaze compared to the reverse shift (Experiment 1). In Experiment 2 we further investigated this effect by manipulating eye gaze independently of its occurrence (relative to the action effect) in the time course of a trial. This second experiment shows that eye contact leads to enhanced intentional binding independent of whether direct gaze is presented before the action or as a result of the action. In a control experiment, similar to Experiment 2, we ask participants to estimate time intervals for sensory events only and we found no effects of eye gaze on time estimations. Overall, our results suggest that gaze direction impacts the intentional binding effect. Interestingly, the effect of eye contact on intentional binding was restricted to specific time intervals. In Experiment 1 we observe an effect in the shortest time interval (300 ms). In Experiment 2 we observe the effect for the time interval of 500 ms.

Eye contact is a specific form of social stimulus that has a wide range of social functions (Emery, 2000). Importantly, it has been demonstrated to increase self-referential processing (Carver & Scheier, 1978, for a review see Conty et al., 2016). In fact, experimental research on the self has been often carried out with paradigms where the attention of participants has been turned to themselves. For instance, by placing someone in front of a mirror (Ainley et al., 2012; Carver & Scheier, 1978), using a camera turned to the participants (Davis & Brock, 1975) or by including the presence of someone (Carver & Scheier, 1978). All these manipulations involve being observed either by oneself or by someone else. More recent studies have confirmed the self-referential power of eye contact (Baltazar et al., 2014; Hietanen & Hietanen, 2017; Pönkänen et al., 2011). This emerging set of studies suggests that eye contact can increase self-processing and consequently elicits increased self-awareness. Eye contact would induce attention toward the self and trigger a self-centered frame of reference for cognitive processing (Conty et al., 2016). In the context of our study, we speculated that direct gaze, because of its influence on self-referential processing, would impact on SoA. Interestingly, the very concept of SoA is related to the self-concept. Experiencing agency only makes sense if one is the agent of an action. Given this central role of the self for SoA it is surprising that little research has been carried out to relate the self-concept to SoA. Our study, thus, adds evidence to the notion that eye contact can affect other self-related processes such as the sense of agency.

Currently it is acknowledged that the sense of agency is modulated by predictive processes as well by postdictive inferences (see Synofzik et al., 2013 for a review). While the former takes the form of sensorimotor processes that inform fluency of actions (Wolpert, Ghahramani, & Jordan, 1995; Frith, Blakemore, & Wolpert, 2000), the latter describe inferential processes where agency is constructed after actions are performed (Wegner, 2003). In our study, we observed that the effects of eye contact occur both before and after the action (experiment 2) and thus, we can't favor any of these two mechanisms. Since eye contact induces a generalized state of self-referential processing, one possibility is that the effects of eye contact on the SoA might be related to changes in arousal. It is well known that eye contact can increase arousal (Nichols & Champness, 1971; Strom & Buck, 1979), and this effect could potentially induce self-awareness. The idea that eye contact effects in our experiments could take place through arousal is convergent with previous findings showing larger intentional binding with increased levels of arousal (Wen et al., 2015). We must however recognize that, as noted by Conty et al. (2016), arousal cannot explain all the effects of eye contact, among them, increased self-awareness. In fact, the study of Baltazar et al. (2014) demonstrated effects associated with eye contact which were independent of arousal. Furthermore, in Experiment 1 eye contact was presented in both conditions. The only difference was that in one condition eye contact was induced by the action and in the other it was preceding the action. Hence, an interpretation based only on arousal for the influence of eye contact on SoA is unlikely.

Our findings might also be related to attentional consequences of being exposed to relevant psychosocial stimuli. Higher attentional allocation for some stimuli (like direct gaze) might have induced participants to better estimate time intervals. This could reduce time-judgements errors (and thus increase intentional effects) for conditions involving direct gaze. However, there is previous literature showing differences between time estimation and intentional binding that argues against this confound. There is an ongoing debate about the crucial components of intentional binding. Some arguing that voluntary actions are essential, while other arguing the causal relationship between action and effect is the more important ingredient (for a review see Moore & Obhi, 2012). Causal inferences are based on properties of an action-outcome relationship such as contiguity. Contiguity refers to the temporal proximity of the action and the outcome. The closer together in time these events appear the stronger the inferred causal relation (Hume & Selby-Bigge, 1888). Thus, causal estimations would directly reflect estimations of time without the involvement of actions. Cravo et al. (2009) used a Michotte paradigm where participants controlled the launching of a stimulus. Participants were then asked to estimate time and causality between collisions of two circles. This study shows that measures of intentional binding (time estimations for voluntary actions) were dissociated of causality estimations. In our study we provide further evidence against the idea of a general effect of gaze on time perception by running a third experiment. In this experiment participants were asked to judge time intervals (and not perform any action) between two visual events. We found no effect of gaze on time-judgements errors. There was only a main effect of interval which was modulated by order. This control experiment renders it very unlikely that our effects of eye gaze on intentional binding are related changes in time estimation. More importantly, our results suggest that the action component is crucial for the modulation of eye gaze on SoA. Thus, considering the complete set of experiments we found that modulations of intentional binding by gaze perception arises for trials involving action execution and direct gaze. It is worth of notice that in our control experiment time-judgement errors were overall reduced relative to the two previous experiments. By definition, voluntary movements should elicit increased time-judgements errors as reflect of intentional binding. In the control experiment there was no action involved, but some time-judgement errors may arise due the presence of highly temporally-correlated events. Our findings of reduced time-judgements errors in the control experiment relative to our previous experiments converge with previous literature. It has been shown that an increase of time-judgements errors might occur but is attenuated for highly temporally-correlated events when no voluntary action is performed (Buehner, 2015). Altogether, changes in time estimations cannot explain intentional binding effects. In order to produce intentional binding both causality and intentional actions must be present. Our findings suggest that gaze perception has a strong impact on agency, but that this effect depend upon action execution.

In Experiment 1 intentional binding was increased for the Averted-Direct compared to the Direct-Averted transition. Since both transition conditions include a direct gaze display, one could have expected no difference between these conditions. However, it is possible that the Direct-Averted transition, which involved a first display of direct gaze, might have elicited self-referential processing, but when replaced by a display with averted gaze, this self-referential processing was overridden by the reorienting effect of averted gaze. There is indeed ample evidence of the attention orienting effects of averted eye gaze (e.g. Driver et al., 1999; Frischen, Bayliss, & Tipper, 2007 for review). This hypothesis is in line with Experiment 2 where direct gaze induced increased intentional binding irrespective of its position regarding the transition. When direct gaze is followed by a mask it produces increased intentional binding relative to averted gaze. For trials with direct gaze, the effect of eye contact is not overridden because this stimulus is not followed by a reorienting cue such as averted gaze.

We observed a strong effect of interval on intentional binding for both experiments. It has been previously recognized that tasks involving time estimation or reproduction are associated with underestimation of time intervals, with these effects increasing proportionally with interval length (Caspar, Cleeremans, & Haggard, 2015; Humphreys & Buehner, 2009; Kühn, Brass, & Haggard, 2013). Some authors suggest that this results from a slowdown of an "internal clock" which predicts action outcomes, and which increases with interval length (Humphreys & Buehner, 2009, 2010; Wenke & Haggard, 2009). Here, we used the distinct intervals to create variability in the responses, but we found that intentional binding occurs for specific action-outcome intervals in the experiments 1 and 2. Experiment 1 showed increased intentional binding due to eye contact for 300 ms-intervals only, while in experiment 2 this occurred for the 500-ms interval only. We had not a-priori hypotheses about when the time-judgement error should be the largest. In consequence, we can only speculate why it was maximal for the 300 ms interval in Experiment 1 and 500 ms in Experiment 2. The lack of effects in the 500 and 700 ms range in Experiment 1 may be related to the fact that in our paradigm the participant anticipated the display of eye contact for Averted-Direct transitions and this expectation was fulfilled the most when eye contact was the fastest (for the 300 ms interval), inducing then a larger intentional binding effect. Another possibility might be related to natural properties of eye gaze changes. When exploring our environment typical saccades range between 20 and 250 ms (Rayner, 1998). It is reasonable to think that we may be more sensitive to eye gaze shifts that occur within the range of natural eye movements. In the second experiment, the stimuli were somewhat different. Participants were confronted with visual stimulus changes rather than gaze changes. Differences in the time intervals where we found the effects might be related to the stimulus differences in the two experiments. Using a design where we varied gaze and order independently makes difficult to predict whether eye contact would be displayed, and thus there might have not been expectations for changes in the shortest interval of 300 ms. Another possibility might be related to the display of eyes masked by sunglasses rendering the stimuli ambiguous: the gaze could be either averted or direct. This could have distracted the participants and result in an overestimation of the time when action-outcome interval was the shortest. However, this does not explain why the changes were seen at the 500 ms interval only in the experiment 2. The nature of this experiment was quite distinct. In this experiment the transition involved a change in relatively central portion of the image rather than a change restricted to the eye gaze direction. There was no dynamic eye gaze shifts, but rather changes of images depicting static eye gaze displays. These displays were devoid of dynamic gaze information. One could putatively say that differences arose due to distinct neural systems involved in the processing of static and dynamic aspects of the face (Pitcher, Dilks, Saxe, Triantafyllou, & Kanwisher, 2011). The nature of the changes might have elicited effects that are different from the effects elicited by natural gaze changes to which were are sensitive almost from birth. However, as outlined above, these constitute post-hoc interpretations and we would need to corroborate these effects testing other time intervals and additional manipulations of eye gaze. We believe that the effects we found are purely related to short action-outcome intervals, especially when task ambiguity is reduced as in the first experiment; this would also explain why in both experiments the 700 ms interval was not influenced by gaze direction. Unfortunately, no study to date directly investigated the effects of different time intervals on intentional binding, since completely random delays have been used (Poonian, McFadyen, Ogden, & Cunnington, 2015), or the effects of the intervals were not discussed, or they were excluded from the statistical analysis (Caspar et al., 2015, 2016; Sidarus & Haggard, 2016). The effect of different action-outcome intervals when using time estimation and/or reproduction tasks to test the intentional binding needs to be further investigated to better understand how timing impacts the SoA.

It is interesting to note a previous study that use eye gaze to modulate the sense of agency. The study of Stephenson et al. (2018) asked participants to reproduce time intervals between the appearance of objects and observed eye gaze shifts. Thus, in this study it is leading and making someone to engage in joint attention that produced the intentional binding between gaze actions and subsequent sensory effects (the gaze movements of the perceived face). In our experiment there were no effects derived from ocular actions, but merely from manual actions. In our case, we hypothesized that visual stimulation with a direct gaze display would evoke self-related processing. In line with this idea, it is noticeable that the first image in a trial of Stephenson's experiment was a face looking straight ahead. In the context of joint attention the communicative context is established by an indicator of communicative intent: a verbal cue or eye contact (Emery, 2000). Thus, the occurrence of eye contact sets the communicative stance of behaviors involving eye gaze. However, a control experiment in the study of Stephenson et al. found that the straight gaze was not mandatory to find the effect; what was critical was rather the fact of directing other's eye movements toward an object. In this respect, our effects are of a different nature. Altogether, there is converging evidence in support of a link between either performing or perceiving eye gaze and the sense of agency. These effects might, nevertheless, involve distinct mechanisms.

We note that our conclusions remain speculative and are limited by the fact that we did not directly measure self-awareness (e.g. questionnaires) or arousal (e.g. galvanic skin responses). We base our premises in the cumulative evidence that eye contact increases self-awareness and arousal. A follow-up study should aim at empirically testing how arousal and/or self-awareness are related to the eye gaze manipulation. Our findings are limited to intentional binding effects and it could be argued that they are unrelated to explicit measures of agency. While intentional binding was intended as a proxy of the SoA (for a review see Moore & Obhi, 2012), some studies have found dissociations between intentional binding and explicit measures of SoA (e.g. Saito, Takahata, Murai, & Takahashi, 2015). It has also been shown that with increasing intervals between action and outcome, explicit SoA is reduced while implicit SoA increases (Ebert & Wegner, 2010). Since these two measures have been shown to be dissociated, we cannot predict the extent to which eye gaze may affect explicit measures of SoA and whether this would map into the same timing specificity as in our present findings. This will be interesting to test in future studies. At the same time, it is important to note that explicit measures of SoA are prone to subjective beliefs and contextual cues (Synofzik et al., 2013). Therefore, regarding the features of our study, involving socially relevant stimuli, explicit measures would likely have been more sensitive to individual differences in personality and beliefs. Future studies will need to take these variables into account in order to fully uncover the mechanism through which eye contact modulates intentional binding.

Studies of the impact of eye gaze behavior and the sense of agency might have potential implications for interactions in social contexts. For instance, when we perform actions in social situations, other's eye contact can act as a cue that intensify our feeling of agency and thus of responsibility over outcomes. In this framework, it could be interesting to investigate the impact of emotional expressions when combined with eye contact on the sense of agency.

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Declaration of Competing Interest

None.

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