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Corresponding Author: Dr. Andrew Bayliss,

Corresponding Author's Institution:

First Author: Andrew Bayliss

Order of Authors: Andrew Bayliss; Lisa J Stephenson; Stephen G Edwards; Emma E Howard

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Suggested Reviewers:

Eyes that Bind Us: Gaze Leading Induces an Implicit Sense of Agency

Lisa J. Stephenson, S. Gareth Edwards, Emma E. Howard, & Andrew P. Bayliss

University of East Anglia, United Kingdom

Corresponding author: Andrew P. Bayliss, School of Psychology, University of East Anglia, Norwich, NR4 7TJ, United Kingdom. Email: Andrew.P.Bayliss@uea.ac.uk.

Abstract

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Eyes that Bind Us: Gaze Leading Induces an Implicit Sense of Agency

1. Introduction

The effects our motor system have on the environment need to be accurately detected. Action monitoring in humans gives rise to a *sense of agency* whereby we become conscious of our own actions (Gallagher, 2000). Such actions might be grasping objects or pushing buttons. However, some of the most important actions we execute do not directly affect the non-social, physical world, but do affect the *social* world. That is, some actions lead to changes in other people's actions (e.g. Casper, Christensen, Cleeremans, & Haggard, 2016). One such ubiquitous social action is that when we look somewhere, other humans may spontaneously reorient their own gaze in the same direction, thus establishing joint attention (Frischen, Bayliss & Tipper, 2007). Joint attention is an everyday but important example that shows that, although eye movements cannot directly affect inanimate objects (aside from modern emerging gaze-controlled technologies, Slobodenvuk, 2016), changes in our gaze direction can influence other *people*. Moreover, saccades are the most common action we perform; we foveate a new area of the visual field 3-5 times each second (Schiller, 1998). However, there is little evidence that saccades evoke a sense of agency in a similar way to manual actions. We, therefore, tested whether an implicit sense of oculomotor agency over a conspecific's gaze shift response emerges in joint attention.

Because eye movements are a special form of action, they may not necessarily engage the same mechanisms underpinning agency as those engaged by other effectors. Nevertheless, there is a clear advantage in having robust agency detection systems for social outcomes elicited by our own actions, so a common mechanism that generalises between all effectors and outcome types could also be posited. Efficiently detecting the social effects we have caused may be critical to understanding others' actions and support mental state ascription (Happé, Cook, & Bird, 2016). Thus, the importance of understanding the role for agency in social action is critical for the understanding of social cognition.

There is one recent paper that suggests that people can learn to understand the contingencies between their saccades and a bouncing ball stimulus on a screen (Grgič, Crespi, & de'Sperati, 2016), which is an initial piece of evidence that the effects of saccades can be explicitly self-attributed. However, explicitly measuring sense of agency does not provide a full picture and can be problematic. This is because explicit measures are somewhat limited as self-reported feelings of control over an action depend on the actor's own ability for introspection (Barlas & Obhi, 2013; David et al., 2008; Sebanz & Lackner, 2007). Moreover, as Gallagher (2012) points out, self-agency is not normally something of which we are typically aware. Explicit measures are further criticised for their susceptibility to response bias and impression management (Obhi, 2012). Because of this, an alternative is to measure sense of agency implicitly with a measure that does not ask the participant to introspect about their explicit experience of control. Inferring sense of agency from implicit measures of correlated, potentially underlying mechanisms, has been a revealing approach (Barlas & Obhi, 2013). This can be achieved by exploiting an effect known as temporal binding (Haggard, Clark, & Kalogeras, 2002), whereby perception of the temporal distance between act and outcome is compressed for self-generated acts, and relatively accurate when judging the gap between two non-self-related stimuli (Moore & Obhi, 2012, for a review). This is why the temporal binding effect is theorised to measure an implicit sense of agency (see Haggard, 2017, for review).

Here, we adopt a twofold approach of measuring the sense of agency: temporal binding (which we offer as an implicit measure of agency) and self-reported ratings of felt control (an explicit measure of agency). We considered this necessary because explicit measures and binding effects do not always correlate, suggesting they may not reflect the exact same processes (e.g. Dewey & Knoblich, 2014, but see Ebert & Wegner, 2010, where changes in temporal binding were found to be related to explicit self-reports of agency). This possible dissociation between explicit and implicit agency are incorporated into an optimal cue integration account where implicit agency operates at a sensorimotor level, whilst explicit agency emerges following higher level processing (see Synovik et al., 2013).

Relatedly, sense of agency may arise both from predictive model-based mechanisms and postdictive mechanisms (Blakemore, Wolpert, & Frith, 2002; Haggard, 2017; Synofzik, Vosgerau, & Voss, 2013). According to the predictive model, the sense of agency is produced when there is a match between the predicted and the actual sensory outcome from an action (Blakemore et al., 2002). The retrospective or postdictive model, however, conceptualises a comparison between the action's idea and action's effect and a sense of agency arises if they are similar (Chambon & Haggard, 2013). Moore, Wegner, and Haggard (2009) argued that different, and varied, agency cues are integrated to result in a sense of agency (e.g. consequences of actions and sensorimotor prediction). Moore, Middleton. Haggard, and Fletcher (2012) tested this by exploring whether explicit and implicit agency were modulated differently by sequential patterns of action and outcome. Their results supported a model in which explicit and implicit agency can be thought of as dissociable, but, they argued, the two are not completely independent systems. This is consistent with Synovik et al's (2013) optimal integration cue account in which explicit and implicit agency can both be included. Given this reviewed evidence, we aimed to measure the temporal binding effect associated with an implicit sense of agency and collect self-report explicit ratings of agency as a manipulation check.

The temporal binding phenomenon has been associated with implicit sense of agency over physical actions that cause auditory (e.g. Barlas & Obhi, 2014), and visual outcomes (Cravo, Claessens, & Baldo, 2011). Investigations of interpersonal agency have been more limited, though agency is recognised as a critical aspect of joint action (Sebanz, Bekkering, & Knoblich 2006). Some studies have demonstrated a sense of agency over others' actions during joint tasks (Obhi & Hall, 2011; Pfister, Obhi, Rieger, & Wenke, 2014), and by illusory agent misidentification (e.g. Wegner, Sparrow, & Winerman, 2004). Interpersonal dynamics can modulate agency (e.g. under social coercion, Caspar et al., 2016). Social outcomes of physical acts have been studied by Yoshie and Haggard (2013), who showed that the valence of human vocalisations that served as a consequence of their participants' actions modulated temporal binding (but see Moreton, Callan, & Hughes, 2016). These studies offer some evidence that a *social outcome* from a button press can elicit binding. In one version of this paradigm, participants are asked to replicate the time interval they have just experienced (e.g. Humphreys & Buehner, 2010). We apply this notion of social sense of agency, measured using a time interval reproduction paradigm, to a crucial component of social cognition – joint attention - a key way in which humans communicate.

The above-reviewed binding evidence suggests that the socio-affective consequences of actions are coded in a generally similar way to non-social outcomes. Previous studies have shown saccade control can be guided by action-outcome effects, albeit in a non- social context (e.g Huestegge & Kreutzfeldt, 2012; Riechelmann, Pieczykolan, Horstmann, Herwig, & Huestegge, 2017). Relatedly, one eye-tracking study demonstrated that action-effect associations are made by the oculomotor system within a social context (Herwig & Hortsmann, 2011). Participants learned that their saccades triggered changes to onscreen facial expressions and adjusted their saccade accordingly. When they anticipated their saccade would trigger a smiling face, saccades landed near the mouth region and when they anticipated triggering a frown, saccades landed near the eyebrow region. This revealing finding illustrates how oculomotor actions can be influenced by perceived outcomes within a social context.

The actions studied thus far in the temporal binding literature are mostly restricted to button presses (see Moore & Obhi, 2012, for a review). In joint attention, the initiating act is an eye movement, whereby the gaze leader looks at an object, and a follower orients their attention to the same object (Frischen et al., 2007). Recent work has shown that people more efficiently detect instances when their gaze has been followed (Edwards, Stephenson, Dalmaso, & Bayliss, 2015), and that leading others' gaze has consequences for subsequent interactions with those individuals (Bayliss et al., 2013; Dalmaso, Edwards & Bayliss, 2016). Having one's eyes followed may necessarily involve the generation of a sense of agency over another's congruent gaze response. Indeed, people do explicitly express a feeling of control (Pfeiffer et al., 2012) and naturalness (Bayliss et al., 2013) in such scenarios. Establishing with temporal binding that similar processes underpin implicit agency in social gaze orienting as with physical acts, would be an important advance in our understanding of how social attention operates. Specifically, such a finding could help to explain why noticing that someone else has followed your gaze to establish joint attention is such a powerful experience, despite it being a common occurrence (e.g. Edwards et al., 2015; Bayliss et al., 2013). That is, rather than merely detecting that one's gaze has been followed, we interpret the social response as a causal outcome of our initial action.

Alternatively, it may not be this straightforward. There are also reasons to think that social agency might operate very differently to non-social agency. We have an enormous amount of experience of our physical manipulations of objects in the environment producing temporally contiguous outcomes. For example, when we kick a ball, it immediately moves. Therefore, the temporal window within which we become aware that our actions have produced an outcome are easily predictable. However, when we produce an action in order to elicit an outcome in another person, the temporal contiguity of the outcome has much more variance, making it harder to predict (Kunde, Weller, & Pfister, 2017). For example, a person may not immediately respond to our request to pass us an object nor may they immediately respond to our gaze signals, if their attention was elsewhere. The variance inherent in social interactions is one reason why implicit agency might work differently in social compared with non-social contexts. On the one hand, the variance might mean that temporal binding effects associated with implicit sense of agency might not emerge at all because social agency detection relies on higher-level mechanisms such as Theory of Mind (Premack & Woodruff, 1978) to make sense of social cause-and-effect. On the other hand, the instability of social interactions might actually elicit very reliable effects because of the critical importance of social agency detection, which could be underpinned by a system flexible enough to tolerate the inherent variance. Therefore, whether saccades that cause a social outcome could elicit temporal binding associated with implicit agency is an interesting open question for work both on social cognition and action monitoring.

In two experiments, we tested the hypothesis that gaze leading elicits temporal binding, which is offered as a measure of an implicit sense of agency (see Haggard, 2017, for a review). Participants' time interval reproductions between an object's appearance and an onscreen face looking at that object were compared between two tasks: an active task when a gaze leading saccade was made to the object, and a passive task in which no such gaze leading was performed. Therefore, we predicted that we would find greater temporal binding when participants' eyes were followed to an object (Active Gaze Leading conditions) than when no saccades to the object were made (Passive conditions). Our data are consistent with this hypothesis, providing evidence that an implicit sense of agency, inferred from temporal binding, is generated in the gaze leader when their gaze is followed, establishing joint attention. A third experiment examined whether making an eye movement alone could explain the temporal compression effects found in Experiments 1 and 2, but no reliable effects were detected.

2. Experiment 1

In Experiment 1, participants completed an interval reproduction task under three conditions manipulated within-subjects. In the active task, for which we predicted reliable temporal binding, participants replicated the time interval between an object's appearance, to which the participants were to immediately saccade, and the on-screen face's gaze shift towards the object. As typical for temporal binding paradigms, we compared performance in the 'active' condition with a 'passive' condition in which no action is made by the participant. In the "Passive Face Fixation" condition participants fixated the face throughout. To provide a further control against which to compare any binding effects in the active task, we added a "Passive Phase Scrambled Fixation" condition. Here, we replaced the face with a non-social stimulus. A strength of our design is that participants in all conditions estimated the temporal gap between the same two events – the object appearing and the main stimulus (a face in two of three conditions) changing. In the active condition, participants saccaded after the object's appearance, and were instructed that their saccade was the cause of the on-screen face moving its eyes. We also had participants complete the Autism Spectrum Quotient (AQ, Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), a self-reported measure of autism-like traits. In all experiments, we have reported how we determined our sample size, all data exclusions (if any), all manipulations and all measures.

2.1. Method

2.1.1. Participants

Thirty-two participants (mean age=20.6 years; 2 were men) completed the study in return for course credit. We determined our target sample size by considering our relevant observed effect sizes in a previous study using the interval reproduction task (d_z=.84-1.44; Howard, Edwards, & Bayliss, 2016) and from appraising the wider literature. Anticipating a large effect size d_z = .8, with 1-β = 0.95 at α = .05, would require n = 23. However, it seemed appropriate here to anticipate a potentially smaller effect size than typically observed in temporal binding experiments using non-social actions, given the inherent variance associated with social responses to our own actions. We therefore targeted a sample of n=32, as this is closer to those used by ourselves and others to address similar questions. Participants reported normal or corrected-to-normal vision. Ethical approval was granted by the School of Psychology Ethics Committee, University of East Anglia. All participants were drawn from the Psychology undergraduate programme, were naïve to the aims of the study and gave written, informed consent.

2.1.2. Stimuli

The female face stimulus was a grayscale photograph with a calm expression (280×374 pixels) taken from Bayliss, Bartlett, Naughtin and Kritikos (2011), and had three versions: eyes direct, eyes closed and looking right. The object stimuli set comprised eight objects commonly found in the kitchen (varying in size; see Bayliss et al., 2013). The centre of the face was located 5 cm left-of-centre onscreen. The objects were presented 11.5cm to the right of the face. For one of the three conditions, a phase-scrambled version of the face was produced, comprising a rectangle (280x374 pixels) with two smaller rectangles (37x26 pixels) placed where the eyes would be on the face. The smaller rectangles were phase scrambled versions of the face stimulus' eye regions. Stimuli appeared on a black background and were presented using E-Prime 2.0 software (see Figure 1).

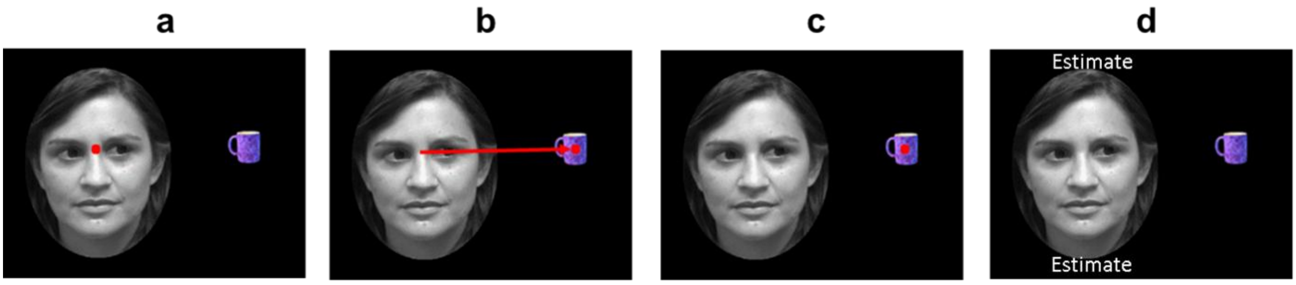

Fig. 1.

Trial sequence for the Active Gaze Leading task. Red circles and the arrow were not displayed but represent where participants were instructed to fixate and the saccade from the face to the object, respectively. Participants looked at the face (a), displayed for 1000ms. Participants made a saccade (b) to the object as soon as it appeared. After a random inter-event interval of 400ms to 2300ms, gaze onset (c) occurred. After 1000ms, estimate instruction appeared (d) until response. Participants pressed and released the space bar to replicate the inter-event interval. The inter-event interval is the time between the object appearing and the gaze onset.

2.1.3. Apparatus and materials

Right eye position was tracked with an infrared eye tracker (Eyelink 1000, SR Research, Ontario, Canada; resolution 0.1^0, 500 Hz). A chin rest was used to maintain head stability. Viewing distance was 70cm from eyes to a 45 cm monitor (resolution 1024×768 pixels). A standard keyboard was used for manual responses. The Autism Spectrum Quotient Questionnaire was used as a measure of levels of autism-like traits (AQ; Baron-Cohen et al., 2001), presented using E Prime. A 1-8 scale was used for participants' self-reported feelings of agency in each condition, with 8 representing the highest feeling of agency.

2.1.4. Design

The within-subjects design had three blocked conditions of 56 trials per task. Block order was counterbalanced across participants. There were six possible orders with six participants experiencing one order, six participants undergoing another order, and the remaining four orders had five participants each. The conditions were Active Gaze Leading, Passive Face Fixation and Passive Phase Scrambled Fixation. The dependent measure was the proportional reproduction error (RE), calculated by dividing the reproduced time interval by the actual time interval to calculate mean proportional reproduction. Thus, 100% reproduction would be reproduction with no error at all. The inter-event interval was the time between an object's appearance and a subsequent on-screen gaze shift (Active Gaze Leading and Passive Face Fixation) or a spatial shift (Passive Phase Scrambled Fixation condition) towards the object. The temporal gap between the object's appearance (rather than the saccade) and the face's response was used to allow direct comparison between all conditions (as no saccades are made in passive conditions). We also had a correlational design to examine any associations between levels of AQ and degree of temporal binding.

2.1.5. Procedure

Each experimental block commenced with a standard nine point eye tracking calibration, then 8 practice trials, then 56 experimental trials (see Figure 1). In the Active Gaze Leading task, for which we predicted reliable temporal binding, each trial began with the presentation of the face on the left side of the screen, looking straight ahead. Participants were instructed to look at the face (presented for 1000 ms) until an object appeared on the right of the face. This sudden onset was the participant's cue to immediately saccade to it. Participants were told they must fixate on the object as soon as it appeared in the Active Gaze Leading task in order to cause the face to follow their gaze. Participants were instructed to fixate on the object after their gaze leading saccade, until the gaze shift occurred. After a randomly selected inter-event interval of 400-2300ms following the onset of the object, the face's gaze shifted to the right to look at the object. Participants were given no further instructions about where to look after their gaze leading saccade, apart from that they must maintain fixation on the object until the gaze shift occurred. After 1000ms, the word "Estimate" appeared (white font, Courier, 18pt) above and below the face. This prompted the participant to manually press and hold down the spacebar for a duration that to their best ability replicated the time interval between the object's appearance and the face's gaze shift towards it. Participants were given no feedback about their responses. Finally, after releasing the spacebar, the display cleared to black for 1000ms.

To be clear about the particulars of this 'Active' Gaze Leading condition, participants were told that their rapid saccade to the object was the causal event that made the face's eyes follow theirs. We were able to confirm that this was the impression that participants had with the explicit agency ratings task (details in Results section 2.2.2). We relied on the low variance of saccadic RT and spatial acuity in this very simple eye movement task to ensure that the minimum temporal gap of 400ms was greater than the vast majority of saccades. Moreover, timing the temporal gap from a single fixed onset that occurred in all conditions (the object onset) afforded us a straightforward and direct comparison across conditions.

The first control condition, in which we predict accurate temporal reproduction, was the 'Passive Face Fixation' task. This was identical to the Active Gaze Leading condition, except that 1) the participant maintained fixation throughout on the face, and 2) the face had closed eyes at the start of each trial before looking to the right following the appearance of the object. The final control condition, Passive Phase-scrambled task, used a rectangle comprised of the phase scrambled face, with two smaller, phase scrambled rectangular regions, which provided a spatial shift towards the object, instead of a gaze shift. The phase scrambled rectangles, positioned in the place the eyes would have been, shifted 2mm to the right after the inter-event interval. The size of the 2mm spatial shift was chosen as this was the same spatial shift as the eyes moved in the Active Gaze Leading condition. In both these passive control conditions, participants were instructed to fixate the face/phase-scrambled face throughout each trial, and replicate the interval between object onset and averted gaze onset. It was emphasised to them that they were not causing the gaze shift to occur. After each task (at the end of a 56 trial block) participants self-reported their degree of felt control over the face's eye movements or the rectangles shifting. The instruction was "Please rate how much control you felt over the onscreen face's eye movements/rectangles shifting from 1 to 8, 1 meaning no control at all to 8 meaning a lot of control." Finally, participants completed the AQ on the computer.

2.2. Results

2.2.1. Proportional Reproduction

Trials in which participants' estimates were 3*SD*s above or below their individual means were removed (0.41% of trials). Mean proportional reproduction was calculated for each participant in each condition and submitted to statistical analysis (see Figure 2). We divided the reproduced time interval by the actual time interval to calculate mean proportional reproduction. Therefore, 100% reproduction represents perfect accuracy, anything greater than 100% is over-reproduction, and less than 100% is temporal compression (under-reproduction). We report Greenhaus-Geisser corrected degrees of freedom when applicable. Confidence intervals and standard errors around the means are based on 1000 bootstrap samples. We report confidence intervals around effect sizes and have used ESCI (Exploratory Software for Confidence Intervals) to calculate these (Cumming & Calin-Jageman, 2017).

First, in order to establish whether each condition produced temporal compression (reliable under-reproductions of the time between object and gaze onset), or relatively accurate reproductions, we performed single sample *t*-tests for each of the three conditions using proportional reproduction. This showed that temporal compression was only statistically significant in the Active Gaze Leading condition. Here, participants reproduced M=84% of the veridical time interval, 95% CI [73, 96] (SD=32%), $t(31)=2.76$, $p=.01$, $d_z=0.69$, 95% CI [0.18, 1.19]. In the two passive conditions, reproduction errors (REs) were low and did not differ statistically from 100% reproduction (Passive Face Fixation condition: M=100% reproduction, 95% CI [91, 112], SD=30%, $t(31)=0.09$, $p=.926$, $d_z=0.02$, 95% CI [-

0.51,0.47]; Passive Phase-scrambled, *M*=94% reproduction, 95% CI [82, 100], *SD*=30%, *t*(31)=1.09, *p*=.286, d_z=0.27, 95% CI [-0.22; 0.76]. There was a main effect of task, *F*(1.53,47.42)=10.91, *MSE*=207, *p*<.001, η_p^2=0.260, and follow-up contrasts showed that the proportional temporal compression effect in the Active Gaze Leading condition was greater than in both the Passive Face Fixation, *t*(31)=3.73, *p*=.001, d_z=0.52, 95% CI [0.21,0.82] and Passive Phase Scrambled Fixation conditions *t*(31)=3.17, *p*=.003, d_z=0.32, 95% CI [0.10,0.52]. Therefore, our hypothesis that having participants' deliberately-initiated saccade *followed* would result in greater temporal compression than passive conditions (where no saccades were made) was supported.

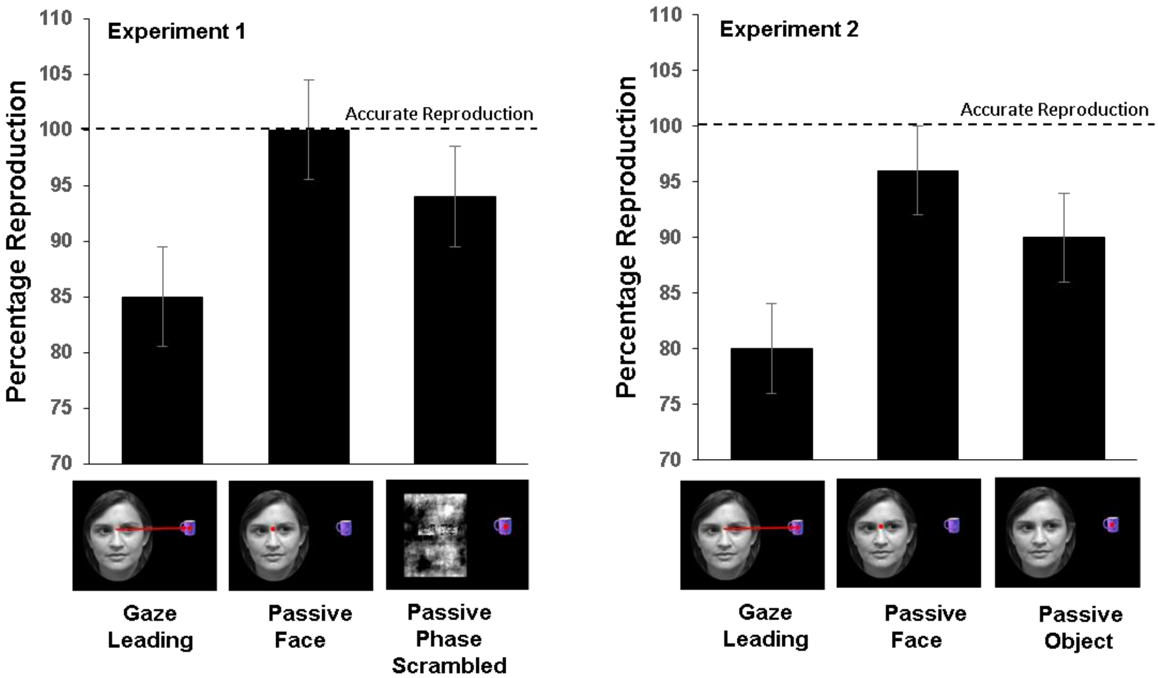

Fig. 2.
Mean percentage reproductions by condition for both experiments. In Gaze Leading tasks, participants looked first at the face, and then at an object as soon as it appeared. In the Passive Face or Passive Phase Scrambled tasks, participants looked at the face or scrambled face throughout. In the Passive Object task (Experiment 2), participants looked at the placeholder/object throughout. The images show how the face/scrambled stimulus was displayed when gaze onset occurred. Red circles and the arrow were not displayed but represent where participants were instructed to fixate (and the saccade from the face to the object for the Active tasks). Error bars represent the standard error of the mean for within-subjects designs calculated using the procedure recommended by Loftus & Masson (1994).

2.2.2. Secondary measures, manipulation checks, and participant subset analyses

Mean self-reported explicit ratings of agency were greater for the Active Gaze Leading (*M*=4.44, *SD*=2.09), than both the Passive Face Fixation (*M*=2.25, *SD*=1.61) and Passive Phase Scrambled Fixation (2.03, *SD*=1.43) conditions; *t*'s>6, *p*'s<.001, d_z's>1. This shows that participants felt a degree of explicit agency in the Gaze Leading condition, supporting our inference that the temporal binding effect presented here reflects a sense of agency. The mean AQ score was 16.59 (*SD*=5.58), which is normative, and did not correlate significantly with reproduction error in any condition (*r*< -.15, *p*>.4).

We also considered potential concerns that something about performing a saccade per se might explain our data. Saccades can, indeed, affect time perception; a substantial amount of work has demonstrated an expansive effect (chronostasis; see review by Merchant & Yarrow, 2016), which if present in our data would of course increase our participants' estimates (i.e. this effect, if present, would work in opposition to our predicted and demonstrated effects). However, two studies have noted an opposing compressive effect (Morrone, Ross & Burr, 2005; Yabe & Goodale, 2015). These opposing effects are small and of similar magnitude so would cancel each other out were they to be present in our (rather different) task, so are unlikely to account for our data. In the critical Active Gaze Leading condition, mean saccadic reaction time was 220ms (*SD*=41ms) and mean saccade duration was 81ms (*SD*=44ms).

Further data exploration included checking for saccades executed after the onscreen face had moved its eyes, which was possible in our design. This could happen, for example, if the participant was rather slow on a trial with a short time interval. This could potentially affect the way that the participant perceived the agency of the social context. Such occurrences were present in nine participants, and on a maximum of three trials for a given participant (and a total of 0.7% of active trials). We reanalyzed the explicit and implicit data excluding all nine of these participants and found that the data pattern was very similar without these participants. Their mean explicit ratings are not different to those who never experienced this (*M*=4.5, *SD*=2.22 and M = 4.41, *SD*=2.15, respectively). Temporal compression was only statistically significant in the Active Gaze Leading condition. Here, participants reproduced *M*=84%, 95% CI [74,95] (*SD*=30%), of the veridical time interval *t*(22)=2.49, *p*=.02, d_z=0.73, 95% CI [0.13,1.3]. In the two passive conditions, reproduction errors were low and did not differ statistically from 100% reproduction, Passive Face Fixation condition: *M*=103%, 95% CI [93,113] *SD*=23%, *t*(22)=0.597, *p*=.556, d_z=0.18, 95% CI [-0.75,0.40]; Passive Phase-scrambled, *M*=98%, 95% CI [87,109], *SD*=25%, *t*(22)=0.31, *p*=.763, d_z= 0.09, 95% CI [-0.49,0.67].

To check whether passive tasks were compromised by saccades occurring contrary to the fixation instruction, we also examined erroneous saccades; on only 0.28% of trials were saccades made in error to the object during the Passive Face task and in 0.11% of trials in the Passive Scrambled condition. These few trials are unlikely to have had a critical impact on the data. Thus, overall, saccade metrics cannot parsimoniously explain the observed time underestimation in the Active task at the trial or participant levels.

As this is the first attempt to our knowledge using a temporal binding paradigm with saccades as the action, it is useful to examine whether our data share another commonality often observed in manual tasks in order to inform comparability across effectors. Previous temporal binding research using interval replication or estimation methodologies show stronger effects with longer intervals (Humphreys & Buehner, 2009; Wen, Yamashita, & Asama, 2015). In order to determine whether our data share this latter characteristic of the temporal binding phenomenon, we compared performance of each participant on the longer 50% of intervals they estimated with the shorter 50% of intervals they estimated. In order to establish whether this pattern is present in our data we instead used the *reproduction error* as the measure, calculated in milliseconds as the participants' reproduction of the temporal interval between two events minus the veridical temporal interval (rather than the proportion error used in the main analysis). The temporal compression effect was larger with the longer intervals, $t(31)=10.27$, $p<.001$, $d_z=1.75$. This corroborates the notion that the observed data reflects a temporal binding effect, rather than some form of previously unreported saccade-induced temporal discounting effect that would most likely be either proportional to saccade metrics, or in fact be stronger for short intervals, not weaker (given the timescale of saccades, and the timescale of previously observed interactions between saccades and time perception). We can, therefore, confidently assert this effect is temporal compression of a similar nature to that previously observed following manual actions that cause physical outcomes.

2.3. Discussion

Participants reliably under-reproduced the temporal gap between an object appearing in the periphery, and an on-screen face responding by looking towards the same object, only when participants moved their eyes to that object in the belief that they caused the face to follow their eyes. This is an indication that participants' eye movements resulted in an implicit sense of agency, the magnitude of which compares to temporal binding paradigms using manual actions that cause changes to the physical environment (Moore & Obhi, 2012). In both of our passive control conditions, our participants did not move their eyes to cause a social response, and they were rather accurate in their time reproductions. Therefore, we can be confident that the eye movement in the critical gaze leading condition caused the temporal compression associated with an implicit sense of agency.

3. Experiment 2

In Experiment 2 we sought to replicate the temporal binding effect in the Active Gaze Leading condition. It is notable that the Passive Face Fixation condition from Experiment 1 involved a face with closed eyes, whereas the Active Gaze Leading condition began the trials with direct gaze. This leaves open the possibility that this initial social contact of direct gaze is critical. To explore this, in Experiment 2, we instead had the active condition begin with closed eyes, and two passive control conditions begin with open eyes. One of the passive control conditions replicated that of Experiment 1, with face fixation throughout. The new passive control condition had participants gaze at the object throughout the trial, which allowed us to examine the importance of end-state gaze location. This was because we sometimes have our gaze followed after deliberate gaze leading, but we also have gaze followed incidentally when we happen to have been observed looking at an object. This is a scenario which is specifically found in a joint attention interaction, that is, gaze can be followed after deliberate gaze leading, but joint attention can result from a person following our passive attention to an object of interest, without any deliberate intention to engage in joint attention. It is, therefore, possible that agency may be experienced during joint attention when our gaze is followed incidentally, without a deliberate, gaze leading saccade. The new control condition enabled us to explore this possibility.

3.1. Method

A new sample of participants (*n*=32; mean age=19.7 years, four were men) was recruited from the same population as Experiment 1 and took part in return for course credits. The same stimuli were used as Experiment 1. The design involved changes to the three task conditions. The Active Gaze Leading condition was the same as Experiment 1 except that the onscreen face began each trial with closed eyes. The Passive Face Fixation task had the face commence with direct gaze. The new third condition, Passive Object Fixation, entailed the addition of a grey fixation dot (Courier, 18pt), which the participants were required to fixate at the start of each trial in this task and was where the object subsequently appeared. Therefore, in this Passive Object Fixation task, the onscreen gaze response occurred when participants were already looking at the object, not having first performed a gaze leading saccade to it. The procedure and task for participants was the same in all other respects for Experiment 2 as the previous experiment.

3.2. Results

3.2.1. Proportional Reproduction

Trials in which participants' estimates were 3*SD*s above or below their individual means were removed (0.28% of trials). The same processing and analysis was performed on the data as in Experiment 1. First, in order to establish whether each condition produced temporal compression (reliable under-reproductions of the time between object and gaze onset), or relatively accurate reproductions, we performed single sample *t*-tests for each of the three conditions on the proportional reproductions. This showed that temporal compression was only statistically significant in the Active Gaze Leading condition. Here, participants reproduced the temporal gap by M=80%, 95% CI [73,86] (SD=19%), $t(31)$=6.18, p<.001, d_z=1.55, 95% CI [0.98, 2.10]. In the two passive conditions, reproduction did not differ statistically from 100% reproduction (Passive Face Fixation condition: M=96%, 95% CI [88, 104], SD=23%, $t(31)$=1.00, p=.327, d_z=0.25, 95% CI [-0.24,0.74]; Passive Object Fixation, M=90%, 95% CI [82,98], SD=22%, $t(31)$=2.70, p=.01, d_z=0.67, 95% CI [0.17;1.18]. There was a main effect of task, $F(2,62)$=21.45, MSE=.221, p<.001, η_p^2=0.409, and follow-up contrasts showed that the proportional temporal compression effect in the Active Gaze Leading condition was greater than in both the Passive Face Fixation, $t(31)$=6.02, p<.001, d_z=0.79, 95% CI [0.46, 1.11] and Passive Object conditions $t(31)$=4.17, p<001, d_z=0.51, 95% CI [0.23, 0.77].

3.2.2. Secondary measures, manipulation checks and participant subset analyses

As in Experiment 1, greater explicit agency was reported following the Active Gaze Leading (3.97, SD=1.79), than both the Passive Object Fixation (2.72, SD=1.57) and Passive Face Fixation (2.59, SD=1.50) conditions (t's>3.6, p<.001, d_z's>0.7). The mean AQ score was 15.06 (SD=6.35), and did not correlate with reproduction error in any condition ($r < -.15$, $p > .4$). In the critical Active Gaze Leading condition, mean saccadic reaction time was 219ms (SD=57ms), and mean saccade duration for the gaze leading saccade was 79ms (SD=69). There were only 0.6% of trials where the onscreen face gaze shift occurred before the participant's saccade was completed. We performed the same check as Experiment 1, by re-analysing the data with the 9 participants excluded who experienced a gaze shift onscreen before their saccade was completed. This was for only an average of 1.22 trials. These nine participant's mean explicit ratings were not different to the rest of the sample (M = 3.66, SD=1.87 and M = 4.01, SD=1.75, respectively). The data showed a remarkably similar pattern. The Active Gaze Leading condition revealed temporal compression – participants reproduced 76%, 95% CI [68,84], SD=19% of the veridical time interval, $t(22)=6.12$, $p<.001$, $d_z=1.81$, 95% CI [1.11,2.48]. The Passive Face Fixation condition did not produce temporal compression (M=92% reproduction, 95% CI [82,101] SD=23%, $t(22)=1.77$, $p=.091$, $d_z=0.52$ 95% CI [-0.07,1.11]. However, the Passive Object Fixation task did reveal reliable under-reproductions, of about one third less than that in the active condition; M=84% reproduction, 95% CI [76,93] SD=19%, $t(22)=3.87$, $p=.001$, $d_z=1.14$, 95% CI [0.51,1.76].

Saccades to the object in error were made on only 0.33% of trials during the Passive Face task. In the Passive Object task of Experiment 2, saccades in error away from the object to the face were made on only 0.06% of trials. Therefore, passive tasks were not compromised by erroneous saccades, just like Experiment 1, as these were so small in number. We ran the same split half analysis of binding by temporal interval as Experiment 1, and again showed larger effects with the longer intervals, $t(31)=14.53$, $p<.001$, $d_z=2.57$, again supporting the notion that these are, indeed, temporal binding effects.

3.3. Discussion

We replicated both the binding effects for the Active Gaze Leading task and the null binding effects for the Passive Face Fixation task. Binding in the Passive Object Fixation task was significantly attenuated compared with the Active Gaze Leading task, but was nevertheless statistically reliable and is worthy of discussion so we address this further in the General Discussion below. For now, we note that there could perhaps be an implicit sense of agency (albeit reduced) which can be generated when there is a shift towards our object of gaze, even if we feel we have only incidentally caused the gaze shift, rather than intentionally.

4. Experiment 3

It is possible that saccades alone - devoid of social or agentic context - could produce binding. However, known saccade temporal disturbances have only previously been demonstrated at short intervals of around 100ms (e.g. Morrone et al., 2005), whilst ours are longer with an average of 1350ms. Nevertheless, it is worth checking if the mere oculomotor act of a saccade can produce similar effects. It is interesting to note that most temporal binding studies do not investigate whether a non-agentic *manual* action might produce distorted temporal judgements in and of themselves. However, because we know that saccades do produce some temporal distortion (Morrone et al., 2005; Yabe & Goodale, 2015), our approach affords an opportunity to explore this fundamental question. However, we also note here that, as our primary interest is in social cognition and agency, we look forward to further work being conducted on this question as it relates to core mechanisms of saccade control and temporal distortions because our single experiment may only provide indicative evidence one way or another. In Experiment 3, therefore, we tested two conditions with no social aspect or agentic expectation and predicted a null effect.

4.1 Method

A new sample of participants executed a saccade of the same amplitude as Experiments 1 and 2 between two fixation crosses in a Saccade task. They began fixation on a first cross and saccaded to a second cross, when it appeared. After the second cross appeared, the first cross enlarged. Participants then reproduced the interval between the second cross appearing and the first cross enlarging. In a No Saccade task, they maintained fixation on the first cross throughout, and reproduced the same time interval as the Saccade task. Thus, participants were exposed to a sequence of perceptual events, but none of these events were social, and they experienced both a saccade task with the same temporal and spatial characteristics of Experiments 1 and 2 and a no saccade task. Furthermore, they were given no information about whether their eye movements were causing anything to occur.

This allowed us to test, for the first time to our knowledge, whether saccades alone – devoid of social context - can elicit temporal binding. A power analysis (GPower: Faul, Erdfelder, Lang, & Buchner, 2007) using the mean gaze leading effects from Experiments 1 and 2, found that *n*=29, would deliver 1-β power=0.95. Therefore, our final sample of n=31 (after removing one participant who did not follow instructions) was appropriate.

4.2 Results and Discussion

We found no significant under-reproduction in the Saccade Task, *M*=94%, 95% CI [79,109] (*SD*=40%), *t*(30)=0.81, *p*=.427, d_z=0.21, 95% CI [-0.29,0.70], nor in the No Saccade task, *M*=105%, 95% CI [95,115] (*SD*=27%) *t*(30)=0.983, *p*=.333, d_z=0.25, 95% CI [-0.75, 0.25]. As our prediction was for a null effect to emerge in the Saccade task, we aimed to assist the interpretability of this null by performing a Bayes one-sample t-test (Rouder, Speckman, Sun, Morey & Iverson, 2009), using the expected effect size parameter as the average effect size from the active conditions in Experiments 1 and 2 of 1.12. This produced a JZS BF=5.82 in favour of the null suggesting that, from these data, the null hypothesis is 5.82 times more likely than the alternative hypothesis. In addition, participants' ratings of explicit agency were low in both conditions; Saccade Task *M*=2.13 (*SD*=1.45) and the No Saccade Task *M*=2.10 (*SD*=1.64). In the Passive Fixation Cross task, saccades in error to the second fixation cross were made on only 0.95% of trials. Taken together, this suggests that the motor act of the eye movement itself is unlikely to account for the temporal compression effects we found in the social context of an interaction with an onscreen face.

5. General Discussion

We investigated the influence of gaze leading on the temporal compression effect known as temporal binding, which is associated with sense of agency. We showed, for the first time, that responses to our eye signals, like other motor actions, produce temporal binding within a simulated social interaction. This is offered as evidence for a form of oculomotor agency, which is informative for the understanding of social attention, and is more broadly of interest to the burgeoning field of technology with gaze-based interfaces (Slobodenyuk, 2016). Across four passive control conditions, we found no binding effects in three and an attenuated binding effect in the fourth. The explicit agency ratings supported our manipulation because greater ratings were made for active over passive tasks. We measured autism-like traits (AQ), but no relationship between binding and these were found. In a further control experiment, where fixation crosses replaced the face and object, we found no binding effects.

Given the importance of joint attention in human social interactions, and the fact that saccades do not - outside of the laboratory, or through certain assistive technologies - cause physical outcomes, it was sensible to first investigate joint attention. As it turned out, our data are typical for the temporal binding literature, so we would in fact predict that intentional saccades that cause a different type of social outcome, or even a non-social outcome, would also produce temporal binding. Our present data can therefore contribute to, and open up new questions for social cognition and for the role of agency in eye movements per se. Given the similarity of our data to that of studies investigating non-social agency, our data are consistent with a common mechanism which attributes agency for social and non-social outcomes. The confirmation that saccades can elicit binding is of general importance for a field in which most of the outcomes resulting in binding are a consequence of a button press (see Moore & Obhi, 2012, for a review). Relatedly, we note that in our active condition, the key saccade was voluntary, and it is therefore an interesting question as to whether or not reflexive exploratory saccades may drive similar agentic mechanisms.

Learned outcomes from saccades when exploring faces can feedback to elicit changes to subsequent interactions (Herwig & Hortsmann, 2011). Taking this together with our data, we can offer a conceptual framework in which agency is experienced for gaze responses, and this may be the mechanism needed for feedback to drive subsequent changes in saccadic behaviour. This would also help explain the changes in visual exploration people exhibit when inspecting faces with which they had previously engaged in joint attention (see Bayliss et al., 2013). This is also consistent with a theoretical framework of sociomotor action control offered by Kunde et al., (2017) whereby the social responses received from our actions feedback to plan subsequent social actions. Experiencing agency over the social responses to our actions is a prerequisite to that process. We need to detect agency over any gaze following we elicit in order to conclude whether we have successfully cued attention to the referent object, in order to then plan the on-going social engagement. Thus, detecting the influence that we have had over others' attentional states may be critical for everyday social interactions and even support theory of mind processes. Determining that mechanisms engaged via physical acts generalise to oculomotor agency adds to what we know about gaze leading in terms of attention (Edwards et al., 2015), and reward value (Schilbach et al., 2010; Gordon, Eilbott, Feldman, & Vander Wyk, 2013). Agency may be a key piece of the puzzle that supports joint action with co-ordination and cooperation (Sebanz & Knoblich, 2009).

The lack of binding in passive conditions shows that the mere presence of a social stimulus does not interfere greatly with accurate timing of intervals per se. However, the weaker but reliable binding effect in the Passive Object Fixation task of Experiment 2 is curious. This observation could merely reflect a carry-over effect from the active task blocks (given our repeated measures design). However, we examined those participants who completed the Passive Object task first, and found that the binding effect was present (M=87% reproduction) and of a similar magnitude to the binding effect for all participants (M=90%), so carry-over effects are an unlikely explanation for the effects we found. Therefore, a more interesting (but speculative) suggestion would be that object-oriented attention in the presence of a face gazing at the same object might affect time estimation, even in the absence of a recently preceding action. It could be the case that if we are looking at an object already, we may attribute some agency to an observed congruent eye shift; but the effect is stronger if we have *recently* saccaded to that object (as in the Active Gaze Leading condition). This chimes with work highlighting the critical importance of objects in joint attention (Bayliss & Tipper, 2006; Bayliss et al., 2013; Lobmaier, Fischer, & Schwaninger, 2006). It is perhaps this aspect of our data that might lead to future research into what might be 'special' about *social* agency – we can cause others to behave in a certain way due to our present state, or even because we have *not* acted. We need to detect these interactions as well. Therefore, there may be a hierarchical system which attributes the greatest sense of implicit agency for intentional gaze leading and then an attenuated sense of implicit agency if a gaze shift is detected when we are already directing our gaze towards an object incidentally. This notion implies the importance of causality, in addition to intentionality, in these effects (Buehner & Humphreys, 2009; Desantis, Hughes, & Waszak, 2012).

There are a host of boundary conditions that remain untested in order to establish the conditions necessary and sufficient to produce indices of implicit agency in social contexts. One important future condition to test is to establish whether the observed gaze response needs to be congruent with the participant's saccadic action, or can be any response (e.g. to avert gaze, or to change emotional expression, for example). We speculate that possibly an incongruent gaze shift might elicit binding if we feel we have caused another to look away from our direction of interest. Whether this would be binding of the same magnitude as a congruent gaze shift (or no binding at all) would be interesting for future studies to explore. The current results identify just one instance in which temporal binding can occur following a causal eye movement. Although determining the specificity of this effect is of course important for understanding the nature of the mechanisms involved, if future work were to demonstrate that the effect does generalise widely, this would not necessarily reduce the direct importance of this mechanism for understanding how social cognition is supported by such basic sensorimotor mechanisms.

One potential complication for the interpretation of our findings is that in both active and passive conditions, participants must detect the onset of the object in their periphery (while they are looking at the face). However, in the active tasks, the onset of the responding gaze shift is to be detected in their periphery because the participant is now looking at the object having performed a saccade, while in the passive conditions, the participant detects the gaze shift at their point of fixation, having not moved their eyes. This difference could have affected the speed of detection of the gaze shift across conditions. However, were participants to be slower to detect the gaze shift in their peripheral vision in the active task, this would have extended their time estimations, which means that our binding effects may have, if anything, been artificially relatively reduced. Despite this difference potentially working against our predictions, medium (Experiment 1) and large (Experiment 2) binding effect sizes emerged.

Another notable aspect of our design is that we used closed eyes for the Passive Face task in Experiment 1 because we wanted to ensure participants could easily identify that the passive task was different to the active task (with open eyes), to ameliorate against potential carry-over effects. In Experiment 2, the face was depicted with closed eyes until averted gaze was displayed – no direct gaze towards the participant. The closed eyes at the outset could be interpreted as less agentic by participants, but this does not appear to be the case as explicit agency ratings were similar in both Experiments 1 and 2, as were the magnitude of binding effects (or even larger observed effect sizes in Experiment 2). We speculate that ambiguity may result in stronger attribution of agency when there is a spatial shift towards our direction of gaze. It may be adaptive to assume that we caused an outcome for which we believe – but are uncertain - that we were responsible for eliciting. The consequences of under-attribution of responsibility for a social outcome could be particularly costly, whilst a little over-self-attribution is unlikely to lead to adverse consequences. This explanation is consistent with recent findings reported by Desantis, Waszak, and Gorea (2016), who found that participants over-attribute self-agency when they are in an ambiguous situation. We suspect that this result may suggest that binding effects will emerge in instances where the end-point of joint gaze occurs (given that joint attention can be incidental, as well as deliberate – both of which are important to notice and interpret). This is another interesting line for future investigations with respect to social agency specifically.

Although the null effects on temporal estimation in Experiment 3 support the notion that the data from Experiment 1 and 2 do reflect a temporal binding effect in a social setting, it is worthwhile considering that one might have expected reliable temporal underestimation even in the context of a non-agentic, non-social saccade task of Experiment 3. Specifically, it is known that eye movements do lead to temporal understimations (saccadic compression, e.g. Morrone et al., 2005), but this did not emerge clearly in Experiment 3 in our data. One explanation for this could be that the known saccadic-driven temporal effects may not be observable in the time intervals of the magnitude we employed here. Our temporal intervals varied around a mean of 1350ms, while the studies that have discovered saccade-triggered temporal disortions have typically employed much shorter intervals (~100ms, e.g. Morrone et al., 2005).

Another potential reason for the failure to observe this temporal compressive effect of saccades per se is possibly due to the action of an opposing temporally expansive process, ‘chronistasis’, which could operate simultaneously under our experimental conditions leading to temporal equilibrium (see Merchant & Yarrow, 2016, for a review and see also Knöll, Morrone, & Bremmer, 2013; Yarrow et al., 2001). Achieving this equilibrium may be advantageous for spatio-temporal perceptual stability, and a naïve assumption would be that such equilibrium would emerge more readily after longer temporal intervals, hence we observed a null effect overall in Experiment 3. This is speculative, however, and it is clear that future explorations of the direct effects of saccades on timing estimates will assist with the contextualisation of our present data, and indeed with other work studying social cognition that involves interactive eye movements and other actions.

Future work could employ a gaze-contingent design to explore agency in social gaze interactions. The present work did not take this approach. If we had yoked more directly the action of the participant to the stimulus changes by using gaze-contingent stimuli, we could have expected our participants to report a greater explicit sense of agency than we found here, and the temporal binding effects might have also been more stable. We did not employ a gaze contingent design here because we wished to avoid the introduction of a confound. Specifically, in the Active Saccade task the to-be-estimated time interval would have included three periods of temporal lag that would not be present in the Passive conditions, making them not comparible without off-line adjustment. These lag periods are the saccade latency, the saccade duration and the eyetracker uptake time to detect good fixation upon the object in order to cause the gaze shift. By not using gaze contingent stimuli, our chosen design afforded direct comparison of actual time intervals across conditions. Nevertheless, it is clear that future studies should employ gaze contingent designs that circumvent the issues we note above to overcome this limitation of the present research. This would allow for even more robust tests of hypotheses regarding the temporal dynamics of social gaze.

We found no reliable correlations between binding effects and autism quotient scores. It may nevertheless be important to test similar paradigms in clinical samples given previous findings of sub-optimality for joint attention initiation (Mundy & Newell, 2007), and decreased temporal binding effects in autism (Sperduti, Pieron, Leboyer, & Zalla, 2014).

Relatedly, it is notable that some forms of psychosis, such as might be experienced by those with a diagnosis of schizophrenia, are associated with disrupted sense of agency (see Haggard, 2017, for a review). Therefore, this may generalise to problems with understanding other's actions, which can be particularly problematic within the social setting of a joint attention interaction. These data are also of direct relevance for developers of gaze-controlled interfaces, a field that is currently grappling with issues of agency and control (Grgič et al., 2016; Slobodenyuk, 2016). For example, our findings can help inform research into making human-robot interactions more naturalistic: when designing robots who can produce eye gaze responses to human gaze signals. Similarly, socially assistive robotics is a growing area where roboticists apply findings from cognitive science to inform the design of therapeutic interventions. Such interventions have been developed for a range of applications, including dementia, mental health, social communication for children with autism and stroke rehabilitation (see Matarić, 2017, for a review). Our research is also informative for developers of gaze-controlled interfaces more generally. Building on the boundary conditions for when eye movements can generate a similar sense of agency as other motor actions do, can inform how to make such technologies acceptable to users. Recent innovations of employing face/eye scanning in smartphones exemplify that using our eyes to control objects will soon be an everyday occurrence, so understanding oculomotor agency in social and non-social contexts is of direct relevance to medical and consumer product development.

To conclude, this study shows for the first time that temporal binding can occur when a social gaze response is perceived to result from intentional eye saccade bids for joint attention. We offer this as an implicit sense of agency effect that follows oculomotor actions that lead to a state of joint attention.

6. Author note

L.J. Stephenson, S. G. Edwards, E. E. Howard, and A.P. Bayliss, School of Psychology, University of East Anglia. Please address correspondence regarding this work to: Dr. Andrew Bayliss, School of Psychology, University of East Anglia, Norwich, NR4 7TJ, United Kingdom. Email: Andrew.P.Bayliss@uea.ac.uk.

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7. Author Contributions

All authors developed the study concept and design. L.J. Stephenson collected and analysed the data. L.J. Stephenson and A.P. Bayliss interpreted the data and drafted the manuscript. All authors provided critical revisions. All authors approved the final version of the manuscript for submission.

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Figure Legends

Fig. 1.

Trial sequence for the Active Gaze Leading task. Red circles and the arrow were not displayed but represent where participants were instructed to fixate and the saccade from the face to the object, respectively. Participants looked at the face (a), displayed for 1000ms. Participants made a saccade (b) to the object as soon as it appeared. After a random inter-event interval of 400ms to 2300ms, gaze onset (c) occurred. After 1000ms, estimate instruction appeared (d) until response. Participants pressed and released the space bar to replicate the inter-event interval. The inter-event interval is the time between the object appearing and the gaze onset.

Fig. 2.

Mean percentage reproductions by condition for both experiments. In Gaze Leading tasks, participants looked first at the face, and then at an object as soon as it appeared. In the Passive Face or Passive Phase Scrambled tasks, participants looked at the face or scrambled face throughout. In the Passive Object task (Experiment 2), participants looked at the placeholder/object throughout. The images show how the face/scrambled stimulus was displayed when gaze onset occurred. Red circles and the arrow were not displayed but represent where participants were instructed to fixate (and the saccade from the face to the object for the Active tasks). Error bars represent the standard error of the mean for within-subjects designs calculated using the procedure recommended by Loftus & Masson (1994).