THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2013
Vol. 66, No. 2, 229–244, http://dx.doi.org/10.1080/17470218.2012.704052

Kinematics matters: A new eye-tracking investigation of animated triangles

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Eye movements have been recently recorded in participants watching animated triangles in short movies that normally evoke mentalizing (Frith–Happé animations). Authors have found systematic differences in oculomotor behaviour according to the degree of mental state attribution to these triangles: Participants made longer fixations and looked longer at intentional triangles than at triangles moving randomly. However, no study has yet explored kinematic characteristics of Frith–Happé animations and their influence on eye movements. In a first experiment, we have run a quantitative kinematic analysis of Frith–Happé animations and found that the time triangles spent moving and the distance between them decreased with the mentalistic complexity of their movements. In a second experiment, we have recorded eye movements in 17 participants watching Frith–Happé animations and found that some differences in fixation durations and in the proportion of gaze allocated to triangles between the different kinds of animations were entirely explained by low-level kinematic confounds. We finally present a new eye-tracking measure of visual attention, triangle pursuit duration, which does differentiate the different types of animations even after taking into account kinematic cofounds. However, some idiosyncratic kinematic properties of the Frith–Happé animations prevent an entirely satisfactory interpretation of these results. The different eye-tracking measures are interpreted as implicit and line measures of the processing of animate movements.

Keywords: Eye movements; Theory of mind; Intention; Motion; Animacy.

An important challenge in social cognitive neurosciences is to obtain implicit measures of human individuals' ability to process and represent social scenes, mental states, and other socially relevant stimuli. Indeed, verbally mediated responses obtained from explicit questions are typically influenced by participants' beliefs and are subject to various biases, while bearing an inconsistent relationship with more automatic and implicit processes (Nosek, Hawkins, & Frazier, 2011). It has

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This study was funded by Agence Nationale de la Recherche (SOCODEV ANR-09-BLAN-0327) and by an APHP–CNRS (L'Assistance Publique–Hôpitaux de Paris–Centre National de la Recherche Scientifique) grant. We thank Uta Frith and Sarah White for kindly providing the animations, and Uta and Chris Frith for their feedback on our results.

therefore been suggested that implicit and explicit processes need to be experimentally distinguished (Frith & Frith, 2008).

A variety of methodologies have been used to try to reach this aim. For instance, some authors have used dual tasks in order to examine residual mentalizing abilities, while neutralizing explicit verbal reasoning (Forgeot d'Arc & Ramus, 2011). Others have measured behavioural interference effects to demonstrate that individual could not help taking into account other people's knowledge (Samson, Apperly, Braithwaite, Andrews, & Bodley Scott, 2010) or their intention to perform a certain action (Sebanz, Knoblich, & Prinz, 2003). Eye tracking also seems a promising technique to give an indirect access to mentalizing processes.

Since the seminal work of Yarbus (1967), who examined scan paths on complex visual scenes, the recording of eye movements has been widely used to explore a variety of cognitive processes. This technique has been particularly fruitful to study social attention. It has been demonstrated that people preferentially look at the face and particularly at the gaze of others (Birmingham, Bischof, & Kingstone, 2008; Foulsham, Cheng, Tracy, Henrich, & Kingstone, 2010).

Animations of abstract geometrical shapes are an example of a set of stimuli initially used for explicit measures of mentalizing but recently used together with eye tracking to obtain more implicit measures. It has been known for a long time that the observation of abstract geometrical shapes such as triangles can induce spontaneous attribution of mental states in verbal reports, depending on the characteristics of their movements (Heider & Simmel, 1944). A series of developmental studies have shown that the ability to interpret simple geometrical shapes as intentional agents simply from their kinematic properties is also present in young infants (see Scholl & Tremoulet, 2000, for a review). One set of stimuli, the Frith–Happé animations, have been widely used in neuroimaging studies (Castelli, Happé, Frith, & Frith, 2000; Gobbini, Koralek, Bryan, Montgomery, & Haxby, 2007; Moriguchi, Ohnishi, Mori, Matsuda, & Komaki, 2007), in studies of autism (Castelli, Frith, Happé, & Frith, 2002; Kana, Keller, Cherkassky, Minshew, & Just, 2009), schizophrenia (Horan et al., 2009; Koelkebeck et al., 2010), and in studies of various other psychopathological conditions (Bird, Castelli, Malik, Frith, & Husain, 2004; Fyfe, Williams, Mason, & Pickup, 2008; Lawrence et al., 2007; Moriguchi et al., 2006; Rosenbaum, Stuss, Levine, & Tulving, 2007). In these animations, a big red triangle and a small blue one move according to three types of scenarios of increasing social and mentalistic complexity. In random animations, the triangles drift randomly and independently from each other. In goal-directed animations, simple intentions such as chasing, dancing, or fighting are manifested by the agents. In theory of mind animations, one character tries to manipulate the mental states of the other with seduction or tricks.

Another line of research on perceptual animacy has attempted to look for the specific motion cues that elicited the perception of goals and intentions. It has been shown that simple intentional movements between two shapes, such as guarding, courting, pursuit, evasion, playing, or fighting, can be accurately classified from basic kinematic properties (Blythe, Todd, & Miller, 1999): Intentions are inferred from indices such as the relative distance between the two agents, their absolute and relative velocities, their relative orientation in the plane, and their absolute and relative rotational velocities. One type of intention has been under particular focus: the chasing of an agent ("sheep") by another one ("wolf"). The percept of chasing largely relies on physical parameters such as temporal and spatial contingency between the changes in direction of the two shapes (Bassili, 1976), the velocity of these shapes (Dittrich & Lea, 1994), the directness of the movement of the wolf toward the sheep (Gao, Newman, & Scholl, 2009), the temporal cohesion of the wolf's convergence toward the sheep (Gao & Scholl, 2011) and the orientation of the wolf toward the sheep (Gao, McCarthy, & Scholl, 2010).

In their review in 2000, Scholl and Tremoulet raised the question of the link between visual attention and the perception of animacy and intentionality. They suggested that eye movements might

play a mediating role in the ability to perceive moving geometrical shapes as intentional. Tracking the eye movements of participants exposed to such stimuli may thus provide an indirect measure of their processing of intentional movement and of agents' mental states. Two previous studies have assessed this question, using the Frith–Happé animations together with eye-tracking measures. The first study found that the mean duration of ocular fixations of normal participants was greater for theory of mind (ToM) than for goal-directed (GD) and greater for GD than for random (R) animations (Klein, Zwickel, Prinz, & Frith, 2009). The authors interpreted their results as an increase in depth of processing with the complexity of the intentions that participants had processed. The second study assessed the spontaneous processing of intentional information in individuals with autism, using another ocular measure: "triangle time" (Zwickel, White, Coniston, Senju, & Frith, 2010). This was calculated by dividing the time when eye gaze fell inside either triangle by the total duration of the animation. Triangle time was longer for ToM than for GD animations and longer for GD than for R animations, and no differences were found between the typical and autism groups. This suggested that, even in autism, visual attention was automatically attracted by intentional movements.

However, there remain alternative interpretations of these results. Indeed these two studies did not take into account the low-level kinematic properties of the triangles. Of course, the fact that all intentions were derived from bottom-up physical information is not in question. One wants to make sure that differences in the ocular measures recorded in the three types of scenario cannot be entirely due to trivial differences in their respective kinematic properties. For instance, it might be that fixation durations increased with the complexity of the scenarios simply because triangles were more often stationary in high-complexity scenarios. Another possibility would be that triangle time increased with scenario complexity because triangles moved more slowly and thus were easier to visually track as complexity increased. It is in fact surprising that no previous study has attempted a quantitative analysis of the kinematic properties of these stimuli.

Thus the purpose of the present study is threefold: first, to evaluate to what extent trivial kinematic differences could underlie the effects reported by Klein et al. (2009) and Zwickel et al. (2010); secondly, to propose alternative eye-tracking measures that would be less contaminated by these trivial kinematic properties; thirdly, to test whether these alternative eye-tracking measures still provide robust indicators of viewers' differential processing of scenarios of different social complexity. We first present the kinematic analysis of the Frith–Happé stimuli, and then we present a new eye-tracking experiment using alternative measures.

EXPERIMENT 1: KINEMATIC ANALYSIS OF THE FRITH–HAPPÉ ANIMATIONS

Predictions

What kinematic properties are likely to affect the ability to follow a visual target? In the smooth pursuit literature, it has been demonstrated that the quality of pursuit decreases when the velocity and the acceleration of the target increase (Lisberger, Evinger, Johanson, & Fuchs, 1981; Mitropoulou et al., 2010; Zackon & Sharpe, 1987). Other suggestions come from the multiple-object-tracking literature. When subjects have to track multiple objects, they use both a target-looking strategy (they successively look at each object and make saccades between them) and a centre-looking strategy in which they look at the centre of the shape formed by the objects and make saccades toward them (Fehd & Seiffert, 2008, 2010). Multiple-object-tracking theory thus predicts that whatever the strategy used, the time spent making saccades will increase with the distance between these objects, leading to a decrease of gaze duration on each object. In the Frith and Happé animations, triangles should therefore be fixated less as the distance between them increases.

Stimuli

We used the full-size version of the 12 Frith–Happé animations (mean duration 34.91 s, *SD* 4.06 s). All animations featured two characters: a small blue triangle and a big red one. They both moved on a white background. In half of the animations, the scene also contained a stationary black rectangle opened on one of its side (symbolizing a house). The four animations of the random condition showed the two triangles drifting about, bouncing on walls as billiard balls. Scenarios of the GD condition included chasing between the two triangles, one triangle following the leading triangle and the two triangles dancing or fighting with each other. The ToM scenarios involved one triangle coaxing, mocking, seducing, or surprising the other.

Method

In order to obtain intuitions about low-level kinematic properties that might differentiate the three types of scenarios, we plotted triangles' trajectories for each scenario in three dimensions. We then focused on physical properties of triangles' movements that could directly explain differences in fixation durations and triangle time.

Visualizing triangles' trajectories

We extracted from each frame of each animation the coordinates of the barycentre of each triangle using an automatic procedure using Image Processing Toolbox 7.0. The accuracy of this extraction was visually checked. We visualized these trajectories on space–time plots in which the horizontal plane represents the horizontal and vertical positions of the triangles in two dimensions, while the vertical axis represents time (see Figure 1).

Two sets of regularities immediately appeared from the visualization of the trajectories:

- There are many more vertical segments in ToM animations than in the others, suggesting that triangles are more often stationary in those scenarios. In contrast, GD animations have flatter trajectories, suggesting high instantaneous velocity.
- Triangles' trajectories tend to be intertwined in ToM animations, due to a small distance between them.

Thus it is possible that participants in previous studies looked longer at intentional triangles because they were easier to track and fixate, rather than because they were more interesting or demanded deeper processing than nonintentional ones. We therefore went on to quantify differences in immobilization time, instantaneous velocity, instantaneous acceleration, and relative distance between triangles, between the three kinds of animations.

Immobilization of triangles

We computed for each triangle in each scenario the immobilization rate—that is, the proportion of frames at which the derivative of the barycentre's coordinates was 0. We then ran a repeated measure analysis of variance (ANOVA) on the immobilization rate with condition (3 modalities: R, GD, and ToM) as between-item variable and the colour of the triangle (2 modalities: blue or red) as within-item variable.

Instantaneous velocity and acceleration

We computed instantaneous velocities and accelerations of each moving triangle at every frame where the triangle was moving (non-null derivative). Thus we obtained a measure of mean velocities and accelerations that was independent from immobilization rate. We then ran repeated measures ANOVAs on these two variables with condition as between-item variable and triangle colour as within-item variable.

Relative distance between triangles

We computed instantaneous relative distances between the two triangles. We then ran repeated measures ANOVAs on these relative distances with condition as between-item variable.

Results

Results are displayed in Table 1. The values of each kinematic parameter for each of the 12 animations are listed in the Appendix.

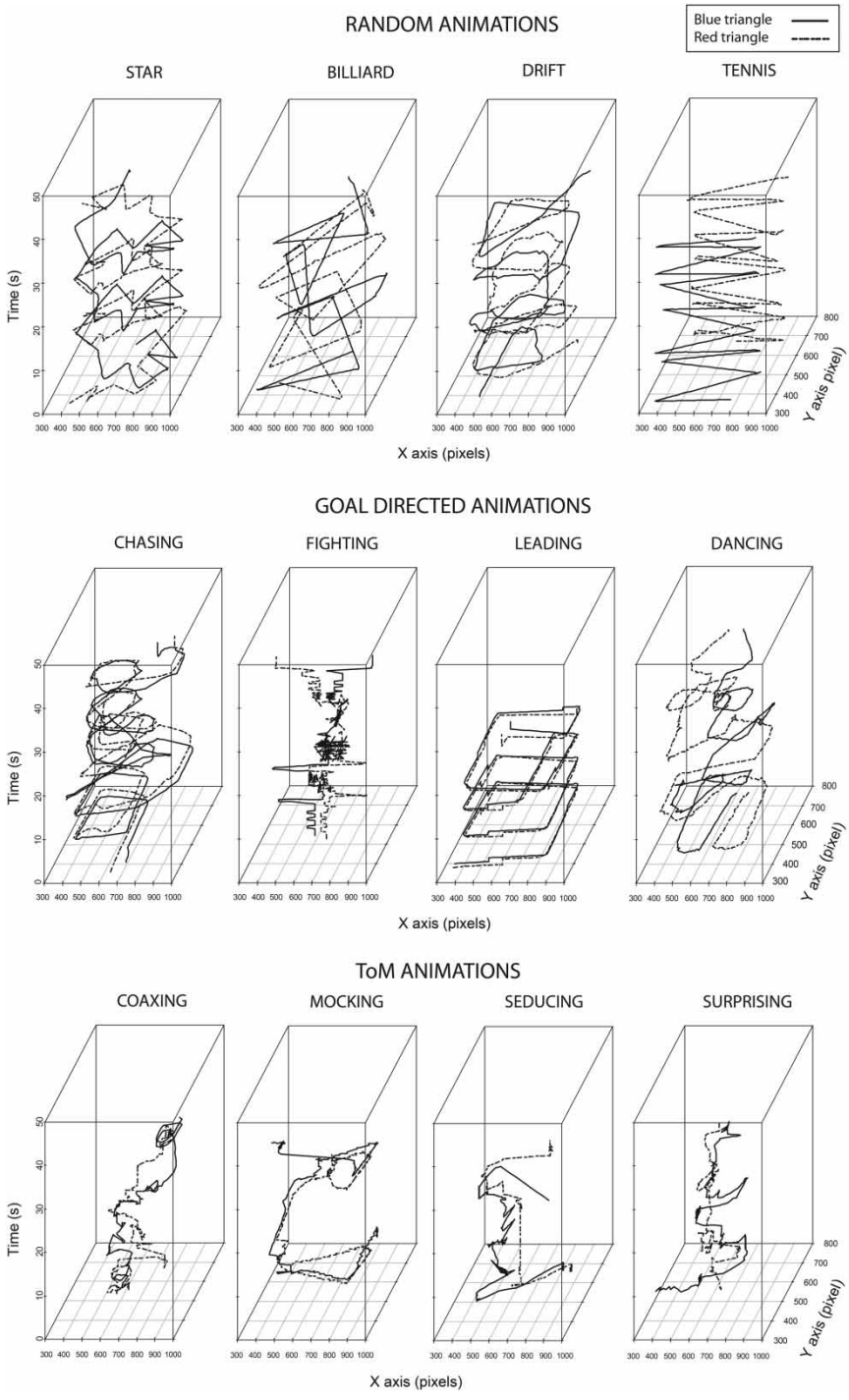

Figure 1. *Three-dimensional space–time plots of triangles' trajectories.*

Triangles' immobilization rate

There were significant effects of condition, $F(2, 9) = 15.74$, $p = .004$, triangle colour, $F(1, 11) = 11.8$, $p = .007$, and an interaction between these two factors, $F(2, 10) = 7.9$, $p = .01$. Pairwise comparisons revealed that immobilization rate was smaller for R animations than for GD animations, Kruskal–Wallis $\chi^2(1) = 5.3$, $p = .021$, and TOM animations, Kruskal-Wallis $\chi^2(1) = 5.3$, $p = .021$. Immobilization rate was not different between GD animations and TOM animations, Kruskal–Wallis $\chi^2(1) = 1.3$, $p = .248$. Immobilization rate was marginally smaller for the blue triangle than for the red one, Kruskal–Wallis $\chi^2(1) = 3$, $p = .083$. No other comparison was significant.

Thus the greater duration of fixation in GD and TOM than in R animations might be at least partly due to greater immobilization rate. This parameter should therefore be controlled in analyses of fixation duration.

Instantaneous velocities

There were no significant effects of condition, $F(2, 9) = 1.9$, $p = .229$, or triangle colour, $F(1, 11) = 0.12$, $p = .738$, and no interaction between these two factors, $F(2, 10) = 0.53$, $p = .604$. Thus this parameter is not expected to explain differences in triangle time or pursuit duration on top of immobilization rate.

Instantaneous accelerations

There was a marginal effect of condition, $F(2, 9) = 3.97$, $p = .08$, and a significant effect of triangle colour, $F(1, 11) = 5.39$, $p = .045$. The interaction between these two effects was not significant, $F(2, 10) = 0.53$, $p = .609$. The red triangle had a greater instantaneous acceleration (mean: 54.9°/s^2, *SD*: 83.9°/s^2) than the blue triangle (mean: 46.8°/s^2, *SD*: 73.4°/s^2). Pairwise comparisons revealed that the instantaneous acceleration of the triangles was smaller for R animations than for GD animations, Kruskal–Wallis $\chi^2(1) = 5.3$, $p = .021$, and ToM animations, Kruskal–Wallis $\chi^2(1) = 5.3$, $p = .021$. Instantaneous acceleration was not different between GD animations and TOM animations, Kruskal–Wallis $\chi^2(1) = 1.3$, $p = .248$.

Thus instantaneous acceleration patterns predict that triangles should be easier to track on R animations than on the other ones. This parameter will therefore have to be controlled for analyses of triangle time and pursuit duration.

Relative distance

There was a significant main effect of condition, $F(2, 9) = 14.6$, $p = .001$. Pairwise comparisons revealed that the relative distance between the two triangles was greater for R animations than for GD animations, Kruskal–Wallis $\chi^2(1) = 5.3$, $p = .021$, and for R animations than for ToM animations, Kruskal–Wallis $\chi^2(1) = 5.3$, $p = .021$.

Table 1. *Kinematic properties of triangles on random, goal-directed, and theory of mind animations*

		Condition						
		Random		*Goal-directed*		*Theory of mind*		
Kinematic property	*Colour of triangle*	*Mean*	SD	*Mean*	SD	*Mean*	SD	p
Immobilization rate (%)	Red	2.5	1.93	31.61	21.14	53.37	11.29	*.004*
	Blue	3.05	2.92	28.98	18.67	38.44	10.44	
Instantaneous velocity (°/s)	Red moving	7.61	1.16	13.57	8.79	6.61	2.26	.229
	Blue moving	7.72	0.96	12.45	6.43	7.12	1.76	
Instantaneous acceleration (°/s^2)	Red moving	24.3	8.09	97.25	41.38	68.05	38.22	.08
	Blue moving	18.43	5.45	82.1	40.34	62.26	23.25	
Instantaneous relative distance (°)		12.70	1.81	8.54	2.04	5.93	1.51	*.001*

Relative distance was marginally greater for GD animations than for TOM animations, Kruskal–Wallis $\chi^2(1) = 3$, $p = .083$.

Thus participants are expected to spend more time making saccades between triangles in ToM than in R animations, which could partly explain the differences reported in triangle time. This parameter will therefore have to be controlled in analyses of triangle time.

Discussion

We have found that the different categories of Frith–Happé animations were matched only on instantaneous velocities. However, there were differences in instantaneous accelerations between conditions. This is consistent with previous findings and may be interpreted as a characteristic feature of self-propelledness (Tremoulet & Feldman, 2000). However, these differences in instantaneous accelerations are unlikely to explain the previously reported differences in eye-tracking measures, as they would predict that it is more difficult to fixate triangles in TOM and GD than in R animations, just the opposite to what has been found by Zwickel et al. (2010).

Another relevant animacy cue is the immobilization rate of the triangles. This was found to be greater for GD and ToM than for R scenarios. It is already known that the presence of discontinuities in the trajectories of moving geometrical shapes increases the experience of animacy (Santos, David, Bente, & Vogeley, 2008). This parameter could explain some differences in eye-tracking measures such as fixation duration and triangle time, which have been previously demonstrated to be larger for animated than for nonanimated triangles (Klein et al., 2009; Zwickel et al., 2010).

We have also found that the distance between the triangles decreased with the complexity of the mental states represented. The attribution of complex mental states implies complex spatial interactions between agents such as sequences of approach and responsiveness between two shapes (Santos et al., 2008), leading to a decrease in their relative distance when they are interacting with each other. Thus, the distance between the triangles is a potential confound of triangle time and might explain why participants looked longer at the triangles in animate than in inanimate conditions.

In summary, our analyses show that the three categories of animations of the Frith–Happé stimuli differ in terms of certain basic low-level kinematic properties. We further suggest that these differences in basic kinematic properties might induce differences in eye fixation patterns, in particular as quantified by mean fixation duration and by triangle time. Thus, when Klein et al. (2009) and Zwickel et al. (2010) report differences in mean fixation duration and in triangle time between conditions, it is not clear that this reflects "depth of processing" or any processing specific to the detection of goal-directed behaviour or mental states. A robot tracking alternately the two triangles might have shown the very same differences on those measures.

Nevertheless, the fact that low-level kinematic properties are confounded with the conditions of the Frith–Happé stimuli is no reason to abandon them. Indeed, it may be very difficult (if not impossible) to manipulate the apparent animacy, goal-directed behaviour or mentalizing of agents without simultaneously altering some of their low-level kinematic properties. Given that such kinematic differences are to some extent unavoidable, the issue rather is that the eye-tracking measures that are presumed to reflect cognitive processing of the social attributes of the animations should not be directly impacted by those low-level kinematic properties, otherwise the differences observed between conditions are open to rather trivial interpretations.

In the second part of this paper, we therefore develop new eye-tracking measures that may be less open to such criticism, and we experimentally test to what extent they may reveal processing differences between conditions that do not trivially reduce to low-level kinematic properties.

EXPERIMENT 2: ROBUST EYE-TRACKING CORRELATES OF MENTALIZING

In this part, we first test whether the eye-tracking measures that Klein et al. (2009) and Zwickel

et al. (2010) used differ between the three types of animations, after controlling for differences in the low-level kinematic properties mentioned in the first part of this paper. For this purpose, we replicate Klein et al.'s experiment and measure eye movements in a group of participants who performed the Frith–Happé triangles task. We then compute fixation duration and triangle time and analyse them with triangles' immobilization rates and relative distances as covariates. Finally, we compute and analyse a new measure, triangle pursuit duration, in order to test whether it is more resistant to kinematic confounds than previous eye-tracking measures.

Method

Participants

A total of 17 participants were recruited (13 females and 4 males). Their age ranged from 19 to 28 years (mean 21.6). All reported to have normal or corrected-to-normal vision.

Material

We used the full-size version of the 12 previously described Frith–Happé animations, 4 in each condition (R: random; GD: goal-directed; ToM: theory of mind).

Animations were displayed on a 17″ monitor (1,280 × 1,024 pixels) on a computer running Matlab with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The participants sat 60 cm from the screen in a dimly lit room. A chin and headrest were used. Eye movements were recorded monocularly with a video-based tower-mounted eye tracker (Eyelink 1000 system, SR research, Ontario, Canada) controlled with the Eyelink toolbox (sampling rate 500 Hz; spatial resolution 1°).

Procedure

Before the beginning of the experiment, the eye tracker was set to obtain the best pupil and corneal reflexion images for each participant. We used the 9-dot calibration routine of the eye tracker, presenting dots one at time in known locations on the screen. Calibration was done before the three training trials and before the 1st, 5th, and 9th test animations. The experiment lasted about 45 minutes. The 12 Frith–Happé animations were presented to each participant in a pseudorandomized order (no more than three consecutive animations of the same condition). Before each animation, a "drift correct" marker was presented in the centre of the screen. Participants were required to look at the dot and press a response button when fixation was attained. This constrained the initial position of fixation and triggered a new calibration if the eye drift was greater than 5°. Participants were instructed to watch the animation attentively because they would be asked to describe what they had seen. They were also instructed to avoid blinking as much as possible during each animation. After each animation, participants were asked to freely describe what they had seen. Their answers were recorded for offline scoring. Positive feedback was given during the training phase, regardless of the answers.

Data analysis

Verbal descriptions

Every recorded description was coded by the same rater on a previously established intentionality scale ranging from 0 to 5 (Castelli et al., 2000). We conducted a repeated measures ANOVA on the intentionality score with subjects as the random factor and condition as within-subject factor.

Eye-tracking measures

Fixation duration. We computed fixations using a dispersion threshold algorithm based on the Salvucci dispersion (Blignaut, 2009). For consistency with previous studies, we used the same parameters as those of Klein et al. (2009) and Zwickel et al. (2010)—that is, that the gaze must stay within a 1.5° radius for at least 100 ms for a fixation to be counted.

We first ran a repeated measures ANOVA on fixation durations with subjects as the random variable and condition as within-subject factor. The aim was to replicate the effect found by Klein et al. (2009) and Zwickel et al. (2010). In order to test whether this effect could be attributed to

differences in the triangles' immobilization rate and in the distance between them, we then ran a repeated measures covariance analysis on fixation duration with the mean immobilization rate of red and blue triangles in each animation and the relative distance between them as covariates.

Triangle time. We considered that a fixation fell within a triangle if it fell within a circle whose centre was the barycentre of the triangle and whose radius was the distance between the barycentre and the furthest corner of the triangle plus 1.5°. Triangle time was calculated as the cumulative duration of fixation within either the blue or the red triangle, divided by the total duration of the animation. In order to replicate the effect found by Zwickel et al. (2010), we first ran a repeated measures ANOVA on triangle time with subjects as random variable and condition as within-subject factor. To address the question of whether triangle time differences might be due to differences in the triangles' immobilization rate and the distance between them, we then ran a repeated measures covariance analysis on triangle time, with the mean immobilization rate of red and blue triangles in each animation and the relative distance between them as covariate.

Mobile triangle time. Because our previous analyses suggested that triangle time differences could be explained by immobilization differences, we designed an alternative measure of triangle time. We computed triangle fixation duration only in frames in which triangles were moving. More specifically, mobile triangle time was calculated as the cumulative duration of eye fixation within either the blue triangle if it was mobile, or the red triangle if it was mobile, divided by the total time during which either the blue or the red triangle was mobile. We first conducted a repeated measures ANOVA on mobile triangle time with subjects as random variable and condition as within-subject factor. We then ran a repeated measures covariance analysis on mobile triangle times with mean relative distance on each animations as cofactor, computed on frames where either the red or the blue triangle was mobile (random factor : subjects; within-subject factor: condition).

Blue and red triangle pursuit duration. Because the triangles tended to be closer to each other in GD and TOM than in random scenarios, we proposed an alternative measure of visual attention devoted to the triangles that would be less likely to be confounded with distance than triangle time: triangle pursuit duration. We used the same rule as that for triangle time to define whether a gaze landed inside a triangle. A pursuit was defined as any instance of the gaze remaining within a given mobile triangle for at least 100 ms. Pursuit duration included all the time when the triangle was moving and was continuously tracked, irrespective of immobilizations. Thus, when the triangle stopped, the pursuit event was not interrupted, but the immobilization duration did not contribute to pursuit duration. The crucial difference between triangle pursuit duration and mobile triangle time is that pursuit duration reflects the duration of continuous fixations on a given triangle, whereas mobile triangle time just reflects cumulative fixation duration on either mobile triangle. Pursuit duration is computed separately for each triangle and therefore may be less affected by how long it takes for the eye to travel from one triangle to the other. We therefore expect that blue and red triangle pursuit durations will not be confounded with their relative distance.

We first conducted a repeated measures ANOVA on triangle pursuit duration with condition and triangle colour as within-subject factors. We then ran two similar repeated measures covariance analyses (statistics F_B and F_R): one on each triangle pursuit duration, with condition as within-subject variable and the mean triangle distance (computed on frames where the target triangle was moving) as covariate.

Results

Verbal descriptions

There was a significant effect of condition on intentionality scores, $F(2, 24) = 190.96$, $p < 10^{-3}$. Intentionality scores were lower for R (mean =

0.13, $SD = 0.28$) than for GD animations (mean = 2.69, $SD = 0.29$), $F(1, 12) = 804.5$, $p < 10^{-3}$, and lower for GD than for ToM animations (mean = 3.36, $SD = 0.74$), $F(1, 12) = 8.83$, $p = .012$.

Eye-tracking measures

Results are displayed in Table 2.

Fixation duration

There was a significant effect of condition on fixation durations, $F(2, 32) = 36.68$, $p < 10^{-3}$. Pairwise comparisons revealed that fixation durations were longer for GD than for R animations, $F(1, 16) = 17.73$, $p < 10^{-3}$, longer for ToM than for GD animations, $F(1, 16) = 25.5$, $p < 10^{-3}$, and longer for ToM than for R, $F(1, 16) = 54.6$, $p < 10^{-3}$.

The repeated measures covariance analysis with immobilization rate and distance as covariates showed main effects of immobilization rate, $F(1, 137) = 8.8$, $p = .004$, and distance, $F(1, 137) = 91.8$, $p < 10^{-3}$. Fixation durations increased with immobilization rate and decreased with distance between triangles. The effect of condition remained significant, $F(2, 32) = 28.6$, $p < 10^{-3}$, and significantly interacted with immobilization rate, $F(2, 137) = 25$, $p < 10^{-3}$, and distance, $F(2, 137) = 23.8$, $p < 10^{-3}$. However, pairwise comparisons showed that ToM did not differ from R, $t(32) = 1.23$, $p = .227$, and GD, $t(32) = -1.55$, $p = .132$, any more once immobilization rate and distance were controlled. The only contrast that remained significant in the covariance analysis was a greater fixation duration for GD than for R, $t(32) = 5.13$, $p < 10^{-3}$. The influence of relative distance on fixation duration was greater for GD than for R, $t(137) = 6.86$, $p < 10^{-3}$, and greater for GD than for ToM, $t(137) = 2.62$, $p = .01$, but not different between R and ToM, $t(137) = -1$, $p = .316$. The influence of immobilization rate on fixation duration was not different between GD and R, $t(137) = 0.86$, $p = .377$, not different between GD and ToM, $t(137) = -0.45$, $p = .653$, and not different between R and ToM, $t(137) = 0.59$, $p = .554$.

Triangle time

There was a significant effect of condition on triangle time, $F(2, 32) = 60.2$, $p < 10^{-3}$. Pairwise comparisons showed that triangle time was longer for GD than for R animations, $F(1, 16) = 44.25$, $p < 10^{-3}$, longer for ToM than for GD animations, $F(1, 16) = 41.65$, $p < 10^{-3}$, and longer for ToM than for R, $F(1, 16) = 75.1$, $p < 10^{-3}$.

The repeated measures covariance analysis with immobilization rate and distance as covariates showed main effects of immobilization rate, $F(1, 137) = 5.7$, $p = .018$, and distance, $F(1, 137) = 4.07$, $p = .047$. Triangle time increased with immobilization rate and decreased with distance between triangles. The effect of condition remained significant, $F(2, 32) = 58.51$, $p < 10^{-3}$, and significantly interacted with immobilization rate, $F(2, 137) = 4.75$, $p = .01$, and distance, $F(2, 137) = 30.2$, $p < 10^{-3}$. However, pairwise comparisons showed that ToM did not differ from GD, $t(32) = -0.95$, $p = .35$, any more once

Table 2. *Eye-tracking measures on random, goal-directed, and theory of mind animations*

		Type of animation					
		Random		*Goal-directed*		*Theory of mind*	
Eye-tracking measure	*Colour of triangle*	*Mean*	SD	*Mean*	SD	*Mean*	SD
Fixation duration (ms)		264.41	45.46	303.03	34.83	339.32	46.85
Triangle time (%)		70.29	10.1	82.62	4.84	91.53	4.53
Mobile triangle time (%)		70.5	9.64	76.19	4.48	82	3.98
Mobile triangle pursuit duration (ms)	Blue	696.2	187.7	972.2	267.5	1177	254.4
	Red	735.5	227.5	812	271	1125.1	327.6

immobilization rate and distance were controlled. The only two contrasts that remained significant in the covariance analysis were greater triangle times for GD than for R, $t(32) = 8.55$, $p < 10^{-3}$, and for ToM than for R, $t(32) = 3.64$, $p = .01$. The influence of triangle's immobilization rate on triangle time was greater in R than in GD, $t(140) = -6.83$, $p < 10^{-3}$, greater in R than in ToM, $t(140) = -5.88$, $p < 10^{-3}$, but equivalent between GD and ToM, $t(140) = 0.65$, $p = .517$.

Mobile triangle time

There was a significant effect of condition on mobile triangle time, $F(2, 32) = 18.91$, $p < 10^{-3}$. Pairwise comparisons showed that mobile triangle time was longer for GD than for R animations, $F(1, 16) = 8.16$, $p = .011$, longer for ToM than for GD animations, $F(1, 16) = 25.36$, $p < 10^{-3}$, and longer for ToM than for R, $F(1, 16) = 24.26$, $p < 10^{-3}$.

The repeated measures covariance analysis with relative distance between triangles as covariate showed a main effect of relative distance, $F(1, 140) = 11.77$, $p < 10^{-3}$: Mobile triangle time decreased with distance between triangles. The effect of condition remained significant, $F(2, 32) = 108.62$, $p < 10^{-3}$, and significantly interacted with distance, $F(2, 140) = 5.31$, $p < 10^{-3}$. However, pairwise comparisons showed that ToM did not differ from GD, $t(32) = -1$, $p = .324$, anymore once distance was controlled. The only two contrasts that remained significant in the covariance analysis were greater mobile triangle times for GD than for R, $t(32) = -3.06$, $p = .004$, and for ToM than for R, $t(32) = 2.29$, $p = .029$. The influence of relative distance on mobile triangle time was greater for GD than for R, $t(140) = 3.26$, $p = .001$, but not different between GD and ToM, $t(140) = 0.92$, $p = .361$, and marginally different between R and ToM, $t(140) = -1.76$, $p = .081$.

Blue and red triangle pursuit duration

There was a significant effect of condition on triangle pursuit duration, $F(2, 32) = 49$, $p < 10^{-3}$, a marginal effect of the triangle's colour, $F(1, 16) = 4.44$, $p = .054$, and a significant interaction between these two factors, $F(2, 32) = 4.13$, $p = .025$. Figure 2 shows that the interaction consisted in a greater difference in pursuit duration between GD and R animations for blue triangles than for red ones. Indeed, pairwise comparisons revealed that the blue triangle pursuit duration was longer for GD than for R, $F(1, 16) = 51.24$, $p < 10^{-3}$, longer for ToM than for GD animations, $F(1, 16) = 10.74$, $p = .005$, and longer for ToM than for R, $F(1, 16) = 76.34$, $p < 10^{-3}$. On the other hand, the red triangle pursuit duration

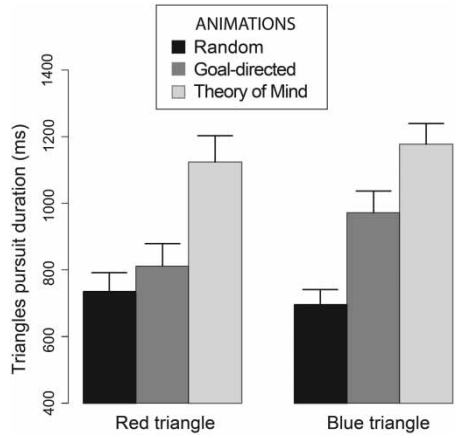

Figure 2. *Mean blue and red triangle pursuit durations on random, goal-directed, and theory of mind animations. Error bars represent the standard error of individual means.*

was longer for ToM than for GD, $F(1, 16) = 23.07$, $p < 10^{-3}$, longer for ToM than for R, $F(1, 16) = 42.3$, $p < 10^{-3}$, but not different between R and GD animations, $F(1, 16) = 1.75$, $p = .205$.

The repeated measures covariance analysis with relative distance between triangles as covariate showed a main effect of relative distance [$F_B(1, 140) = 19.71$, $p < 10^{-3}$; $F_R(1, 140) = 19.02$, $p < 10^{-3}$]: Blue and red triangle pursuit duration decreased with distance between triangles. The effect of condition remained significant [$F_B(2, 32) = 30.77$, $p < 10^{-3}$; $F_R(2, 32) = 18.4$, $p < 10^{-3}$] and significantly interacted with distance [$F_B(2, 140) = 11.68$, $p < 10^{-3}$; $F_R(2, 140) = 6.4$, $p = .002$]. For the blue triangle pursuit duration, all contrasts remained significant in the covariance analysis: The blue triangle pursuit duration was greater for GD than for R, $t(32) = 4.66$, $p < 10^{-3}$, greater for ToM than for R, $t(32) = 3$, $p = .006$, but smaller for ToM than for GD, $t(32) = -2.23$, $p = .032$. Thus, the covariance analysis inverted the direction of the difference between GD and ToM. Furthermore, the red triangle pursuit duration became greater for GD than for R, $t(32) = 2.12$, $p = .041$, and smaller for ToM than for GD, $t(32) = -2.51$, $p = .017$, and the contrast ToM versus R was no longer significant, $t(32) = 0.76$, $p = .452$. Thus the covariance analysis inverted the direction of the difference between GD and ToM for the red triangle pursuit duration as well. The influence of relative distance on triangle pursuit duration was greater for GD than for R [$t_B(140) = 4.70$, $p < 10^{-3}$; $t_R(140) = 42.76$, $p = .007$], greater for GD than for ToM animations [$t_B(140) = 2.25$, $p = .026$; $t_R(140) = 3.03$, $p = .003$], but not different between R and ToM [$t_B(140) = -1.64$, $p = .103$; $t_R(140) = 0.02$, $p = .987$].

DISCUSSION AND CONCLUSION

This study had two aims. The first one was to analyse the kinematic characteristics of the classical Frith–Happé animations and to assess to what extent they might explain differences in eye-tracking measures between the three conditions. The second one was to find eye-tracking measures of the attribution of intentions that were not explained by trivial properties of triangles' movements.

In the kinematic analysis, we found that the three kinds of animations significantly differed in terms of triangles' immobilization duration and triangles' relative distance, so that these properties might be a confound in previous eye-tracking analyses of these animations. Furthermore, in the eye-tracking study, we confirmed (after Klein et al., 2009) that fixation duration differed between the three types of animations. Consistent with our hypothesis, we have shown that fixation duration increased with triangles' immobilization rate and decreased with relative distance between triangles. It is likely that when triangles are stationary or when they are close to each other, there is no need for participants to move their eyes to scan the visual scene, thus leading to an increase in fixation duration. Furthermore, using covariance analyses, we have found that the difference in fixation duration between GD and ToM was entirely explained by low-level kinematic properties such as immobilization rate or distance between triangles. Similarly, we have confirmed (after Zwickel et al., 2010) that triangle time increased with mentalistic complexity of the animations, but we also found that differences in triangle time between GD and ToM were entirely attributable to triangle's greater immobilization rate and smaller relative distance in ToM than in GD animations. Even when we computed triangle time restricted to frames where triangles were moving (mobile triangle time), the difference between GD and ToM animations was explained by the fact that triangles were closer to each other in ToM than in GD animations.

Our new measure of visual attention dedicated to triangles, triangle pursuit duration, also decreased with relative distance between triangles and increased with the mentalistic complexity of the animations. Relative distance between triangles did not entirely explain the difference in blue triangle pursuit durations between R and GD animations: Participants tracked GD triangles longer than R triangles even after controlling for relative distance. Furthermore, triangle pursuit duration also differentiated ToM from GD animations when relative distance was controlled. However,

in this case, triangle pursuit duration became greater for GD than for ToM. This reversal of the effect does not allow for a clear interpretation, other than noting that the GD category is highly heterogeneous (as is evident in Figure 1), so that with just four animations per condition, idiosyncratic features of a given animation are likely to drive inconsistent effects for the GD category. While this heterogeneity is theoretically desirable in order to decouple the conditions from low-level kinematic characteristics, a much greater number of animations per condition would be required to produce consistent effects that are not driven by idiosyncratic features of the animations.

We conclude that triangle time and triangle pursuit duration reflect an attentional capture by animate motion in Frith and Happé animations, irrespective of kinematic confounds. These results are in line with a recent study that demonstrated a capture of visual attention by a self-propelled and self-directed target compared to a mechanical target that underwent exactly the same motion, but in a predictable way (Pratt, Radulescu, Guo, & Abrams, 2010). Thus, these eye-tracking measures could be considered implicit and online measures of the detection of animate motion, in these particular Frith and Happé animations. However, when all low-level kinematic properties are controlled, they do not seem to provide a reliable index of the detection of complex and mentalistic intentions (as opposed to simple intentions such as in goal-directed actions), at least for this specific set of animations.

Zwickel et al. (2010) reported no difference in fixation duration or triangle time between individuals with autism spectrum disorders and control participants. They concluded that "autistic individuals formed similar representations of different degrees of socially intentional behaviour, as revealed in their eye movements" (p. 7). Our present results may suggest a slightly different interpretation. If mean fixation duration and triangle time differences between ToM and GD conditions are attributable to low-level kinematic characteristics of the displays, without requiring the attribution of complex mental states, then it may be expected that individuals with autism will show just the same differences. Thus covariance analyses controlling for low-level kinematic confounds would be necessary in order to draw a firm conclusion on autistic individuals' tracking of socially intentional behaviours.

The use of such eye-tracking measures could also be fruitful in other psychopathological conditions such as schizophrenia. Individuals with schizophrenia have difficulties in the attribution of intentions to others in comic strips (Brunet, Sarfati, & Hardy-Bayle, 2003; Sarfati, Hardy-Bayle, Brunet, & Widlocher, 1999, Zalla et al., 2006), in videos depicting ecological social situations (Bazin et al., 2009; Mehl et al., 2010; Montag et al., 2011) and in Frith–Happé animations (Horan et al., 2009; Koelkebeck et al., 2010; Russell, Reynaud, Herba, Morris, & Corcoran, 2006). In a context where the distinction between implicit and explicit processing is of high interest in schizophrenia (e.g., Linden et al., 2009; Roux, Christophe, & Passerieux, 2010; van't Wout et al., 2007), the eye-tracking technique could help address the question whether deficits in social perception lie in the implicit processing of animate motion or in the ability to make more explicit judgements about such displays.

On top of revealing differences between conditions, our study has also found large differences within condition, both in terms of kinematic properties (see Figure 1) and in terms of eye-tracking measures. For instance, triangle pursuit duration shows large differences between items of a given condition (see standard deviations in Table 2), and this is not compensated by a large number of items per condition. Indeed the three categories of animations represent quite heterogeneous situations, both at the social and at the kinematic levels. This may be suitable for the purpose of rating mentalistic terms in verbal descriptions, but less so for eye-tracking studies. For the latter purpose, it may be more fruitful to rely on more controlled stimuli displaying one particular category of mental states or social behaviours and showing relatively constant kinematic properties, as has been done, for instance, with chasing (Gao et al., 2010; Gao et al., 2009; Gao & Scholl, 2011).

In conclusion, the results of this study show that is possible to obtain implicit ocular measures of the

attribution of animacy using the classical Frith–Happé animations, which are not confounded with low-level kinematic properties of the displays.

Original manuscript received 7 April 2012
Accepted revision received 6 June 2012
First published online 30 August 2012

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APPENDIX

Kinematic properties of triangles for each of the 12 animations

		Kinematic properties						
		Immobilization percentage		*Instantaneous velocity (°/s)*		*Instantaneous acceleration (°/s²)*		
Category	*Scenario*	*Blue*	*Red*	*Blue moving*	*Red moving*	*Blue moving*	*Red moving*	*Instantaneous relative distance (°)*
Random	BILLIARD	3.0	4.6	7.2	7.1	13.7	16.3	13.6
	DRIFTING	2.1	1.4	7.0	6.5	19.6	24.1	11.6
	STAR	7.0	3.5	7.6	7.6	25.6	35.4	10.8
	TENNIS	0.0	0.0	9.1	9.2	14.8	21.4	14.8
Goal directed	CHASE	9.0	12.6	10.1	9.8	45.0	51.6	10.8
	DANCING	16.7	16.7	6.4	7.0	53.3	73.2	9.4
	FIGHTING	41.5	36.2	11.7	11.0	130.9	127.1	6.0
	LEADING	44.0	56.6	21.5	26.5	99.2	137.1	8.1
Theory of mind	COAXING	36.6	48.5	5.7	7.3	49.8	63.7	5.2
	MOCKING	39.5	55.9	8.8	9.5	90.8	122.1	5.3
	SEDUCING	37.3	64.8	8.4	5.3	70.3	53.3	5.0
	SUPRISING	20.4	38.6	5.5	4.3	38.1	33.1	8.2