An eye-tracking investigation of intentional motion perception in patients with schizophrenia

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Background: Schizophrenia has been characterized by an impaired attribution of intentions in social interactions. However, it remains unclear to what extent poor performance may be due to low-level processes or to later, higher-level stages or to what extent the deficit reflects an over- (hypermentalization) or underattribution of intentions (hypomentalization). **Methods:** We evaluated intentional motion perception using a chasing detection paradigm in individuals with schizophrenia or schizoaffective disorder and in healthy controls while eye movements were recorded. Smooth pursuit was measured as a control task. Eye-tracking was used to dissociate ocular from cognitive stages of processing. **Results:** We included 27 patients with schizophrenia, 2 with schizoaffective disorder and 29 controls in our analysis. As a group, patients had lower sensitivity to the detection of chasing than controls, but showed no bias toward the chasing present response. Patients showed a slightly different visual exploration strategy, which affected their ocular sensitivity to chasing. They also showed a decreased cognitive sensitivity to chasing that was not explained by differences in smooth pursuit ability, in visual exploration strategy or in general cognitive abilities. **Limitations:** It is not clear whether the deficit in intentional motion detection demonstrated in this study might be explained by a general deficit in motion perception in individuals with schizophrenia or whether it is specific to the social domain. **Conclusion:** Participants with schizophrenia showed a hypomentalization deficit: they adopted suboptimal visual exploration strategies and had difficulties deciding whether a chase was present or not, even when their eye movement revealed that chasing information had been seen correctly.

Introduction

Schizophrenia is characterized by impairments in several domains of social cognition, including theory of mind or mentalizing, emotion recognition[1,2] and the perception of intentional actions. Initial studies of the perception of intentional actions in schizophrenia were based on the biological motion paradigm, which presents simple animations of human actions portrayed by actors visible only through point light displays.[3] A decreased sensitivity to biological motion has been demonstrated in individuals with schizophrenia.[4] This paradigm allows quantifying the perception of intentional actions in this population using a psychophysical approach. However, it focuses mostly on individual actions as opposed to social interactions. The Frith–Happé animations have been widely used to assess the perception of intentional actions involving social interactions.[5] In these animations, inspired from Heider and Simmel's seminal work,[6] 2 triangles move according to intentional or nonintentional scenarios: in the random condition, the triangles drift and bounce independently like billiard balls, whereas in the intentional conditions, 1 triangle acts intentionally toward the other triangle. Participants are asked to describe what they have seen; convergent evidence shows that individuals with schizophrenia provide less intentional and less accurate descriptions of intentional scenarios than control participants.[7–9]

Overall, research on social cognition in individuals with schizophrenia leaves a number of questions open, including 2 that are our main focus here: Do individuals with schizophrenia show a hypo- or a hypermentalizing deficit? Is their deficit situated at low (early, implicit, automatic) or at high (late, explicit, reflexive) levels of processing?

Hypomentalizing refers to being less able to perceive and infer intentions. In contrast, hypermentalizing involves overattributing intentions, including to nonintentional stimuli. Hypermentalization has been suggested by several authors on the basis of the existence of paranoid symptoms in schizophrenia, leading to an excessive attribution of malevolent intentions to others.[10,11] This hypothesis has received some experimental evidence: for example, individuals with schizophrenia perceived more hostility in ambiguous intentions, and this bias was positively correlated with self-reported levels of paranoia.[12]

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Nevertheless, few studies have attempted to distinguish hypo- from hypermentalizing in individuals with schizophrenia, and the available results are inconsistent. Using the Frith–Happé animations, 1 study found more intentional descriptions of random animations and fewer intentional descriptions of intentional animations in participants with schizophrenia, suggesting that both hyper- and hypomentalizing might be at play.[8] Two other studies replicated the hypomentalization but not the hypermentalization.[7,9] However, studies involving Frith–Happé animations are based on verbal responses: hypermentalizing is intrinsically more difficult to demonstrate than hypomentalizing, particularly in individuals with schizophrenia, since it requires producing more overt responses. It could therefore be that a spontaneous tendency for these individuals to hypermentalize is offset by a general tendency to be underresponsive, thus explaining the heterogeneity of the results. In order to provide a fair test of the hypermentalizing deficit hypothesis, it therefore seems desirable to investigate it using experimental paradigms that make hypermentalizing no more costly to participants than hypomentalizing. It is the case of the Movie for the Assessment of Social Cognition, another test that has been developed to distinguish these 2 hypotheses. Compared with control participants, individuals with schizophrenia made more hypomentalizing but no more hypermentalizing errors when verbal intelligence and verbal memory were taken into account.[13] However, the lack of significant difference in hypermentalization between patients and controls may have been explained by the nature of the stimulus (several characters involved in complex verbal interactions referring to ambiguous mental states) and by the response modality (choice among 4 alternatives) overloading the patients' verbal abilities. Thus a replication of this result is needed on a nonverbal paradigm before drawing a conclusion about hypermentalization in individuals with schizophrenia.

The second question arises from the many stages of processing leading from the perception of a stimulus to the production of a response, such that poor performance in a given social cognition task might be due to deficits at any of these levels. Deficits might arise at low-level stages of perceptual exploration abilities or at early perceptual stages. They might also arise at higher-level cognitive stages of assessing perceptual evidence and selecting a response accordingly or at stages of producing a verbal response. There is supportive evidence for deficits at each of these stages. Evidence that visual exploration of static visual scenes[14] and smooth pursuit[15] are impaired in schizophrenia makes deficits at the exploration stage plausible. A whole section of the literature on schizophrenia is devoted to deficits in basic auditory and visual perceptual processes.[16,17] Finally, verbal difficulties in schizophrenia are well documented.[18]

In order to address these 2 questions and disentangle the many alternative interpretations of poor performance in social cognition tasks in individuals with schizophrenia, we designed a new experimental paradigm with the following properties: hypo- and hypermentalizing responses are equally difficult; no verbal responses are required; smooth pursuit and perceptual exploration strategies can be assessed; and low-level, implicit mentalizing can be to some extent differentiated from explicit and reflexive mentalizing.

For this purpose we used the recently developed chasing detection paradigm,[19] a psychophysical rendering of intentional motion detection restricted to a particular interaction: chasing. Responses consist of a simple 2-alternative forced choice (chase v. no chase) and are thus free from verbal constraints, making it equally easy to over- or underdetect intentional motion. The eye-tracking allows us both to assess perceptual exploration strategies and to obtain an implicit measure of chasing detection in order to distinguish different levels of processing.

Methods

Participants

We recruited individuals with schizophrenia or schizoaffective disorder and healthy controls for participation in this study. Patients were recruited from community mental health centres and outpatient clinics in the Versailles area. The control participants were recruited from the volunteers panel at the Versailles Hospital and Laboratoire de Sciences Cognitives et Psycholinguistique. Exclusion criteria for both groups were substance or alcohol dependence within the 6 months preceding the study and current or prior untreated medical illness, including neurologic illness. The control group was screened for current or past psychiatric illness, and individuals were excluded if they met criteria for any axis I disorder of the DSM-IV-TR. All diagnoses in the patient group were confirmed by 2 licensed psychiatrists (P.R. and each patient's treating psychiatrist) according to the DSM-IV-TR criteria for schizophrenia or schizoaffective disorder. The experiment was approved by the local medical ethics committee (Comité de Protection des Personnes Paris Ile de France XI). All participants received a complete description of the study verbally and in written form. The investigators checked whether patients were capable of giving fully informed consent through specific interviews focused on the ability able to comprehend and retain information about the research and to use and weigh this information to make an appropriate decision. Written informed consent was then obtained from each participant.

Cognitive and clinical measures

General intelligence was estimated using the Wechsler Adult Intelligence Scale (WAIS-III) vocabulary, similarities, pictures completion and matrices subtests. Mean haloperidol equivalent dosage was computed using a standardized method.[20] We rated the severity of schizophrenic symptoms using the Positive and Negative Syndrome Scale (PANSS).[21]

Eye movement recording

Stimuli were presented on a 17-inch display with a 75 Hz refresh rate and 640 × 480 pixel resolution, viewed from 62 cm in a dimly lit room. Eye movements were recorded monocularly (Eyelink 1000 system with remote/head free configuration, SR research) with a sampling rate of 500 Hz and a spatial resolution of 1°. Participants were instructed to avoid blinking as much as possible during each trial (see the Appendix, available at jpn.ca, for details about the eye-tracking calibration procedure).

Smooth pursuit control task

Smooth pursuit deficits have been repeatedly demonstrated in individuals with schizophrenia[15] and might explain decreased chasing detection sensitivity in this population. In the present study, smooth pursuit was assessed on a paradigm that has demonstrated impaired smooth pursuit in individuals with schizophrenia.[22] The complete procedure is described in the Appendix. Participants were presented with a visual target that moved horizontally across the screen with a constant velocity. They were asked to follow the target with their eyes as closely as possible. The gain of smooth pursuit was computed by dividing the mean velocity of the eye by the velocity of the target; a gain of 1 reflects perfect smooth pursuit.

Chasing detection paradigm

The complete procedure is described in the Appendix. Participants were presented with 5 identical moving discs that frequently and randomly changed directions, thus giving the impression that they were self-propelled. In half of the trials, 1 disc, the "wolf," did not move haphazardly like the others; rather, it chased another disc, the "sheep." Nothing other than the sheep-directed motion of the wolf distinguished those 2 discs from the others. When the wolf changed its direction, it converged toward the sheep with a certain chasing efficiency (a parametrically manipulated angular deviation between the wolf's direction and the sheep's position). In easy trials, the chasing efficiency was 0°: the wolf perfectly converged toward the sheep. In trials with medium difficulty, the chasing efficiency was 30°: the wolf could move in any direction within a 60° window that was centred on the moving sheep. In difficult trials, the chasing efficiency was 60°, and the wolf's direction was even less constrained. A screenshot of an animation and an illustration of 30° chasing efficiency are presented in Figure 1. Seventy-eight pseudorandomly ordered trials were completed, with 13 chasing-present trials and 13 chasing-absent trials at each of the 3 levels of difficulty. After each trial, participants indicated whether a chase was present or not by pressing 1 of 2 keyboard buttons. Examples of animations can be watched online at http://sites.google.com/site/paulromainroux/engl.

Nonresponses were discarded from the analysis. To ensure that this exclusion didn't significantly influence the analysis of forced-choice responses, we ran a repeated-measures analysis of variance (ANOVA) on the nonresponse rate with group (patient v. control) as a between-subjects factor.

We ran a signal detection analysis on forced-choice responses and computed measures of chasing detection sensitivity (d′) and bias (lnβ) according to Macmillan and Creelman's formulas[23] (see the Appendix for the detailed formulas). Sensitivity measured the ability to detect chasing, whereas bias measured the tendency to give the chase response more frequently than the no-chase response. A hypomentalizing deficit would predict chasing detection sensitivity to be lower in patients than controls, whereas a hypermentalizing deficit would predict an increased bias toward the chase response.

Visual exploration strategies

We considered 2 visual exploration strategies likely to be adopted by participants trying to detect a chase: either following 1 agent for a certain amount of time (and jumping to another agent until a chase is detected), or looking roughly at the barycentre of all agents, thus obtaining an optimal view of the movements of all agents simultaneously. Such agent looking and centre looking strategies have been shown in multiple objects tracking paradigms where participants have to focus their attention on multiple moving targets.[24,25] In order to characterize eye movement patterns relevant to these strategies, we analyzed the proportion of eye gazes falling on 3 different regions on each sample of each trial (see the Appendix). The agent looking rate was defined as the proportion of eye gazes falling on an agent. The barycentre looking rate was defined as the proportion of gazes falling on the barycentre of the 5 agents. Finally, the stray looking rate was defined as the proportion of gazes falling anywhere else (excluding agents and the barycentre). Because these 3 measures are not independent from one another, we analyzed only barycentre and stray looking rates.

We developed a measure related to the distribution of gaze across the 5 agents: the agent preference index, defined as the standard deviation (SD) of looking rates on each of the 5 agents (see the Appendix). The idea is that if participants detect the chase, they will tend to track the sheep and the wolf and, hence, will show unevenly distributed looking rates across agents and a high SD. On the contrary, if they detect no chase, all agents should have an equal probability of being tracked, and the SD should be lower. Thus, the agent preference index should provide a measure of participants' implicit detection of chasing, independent from the explicit response. Two further sensitivities were derived from the agent preference index using the same signal detection approach as for the chasing detection sensitivity. The ocular sensitivity measures the extent to which the agent preference index reveals the implicit detection of chasing. The cognitive sensitivity measures the extent to which explicit chase responses reflect the implicit detection of chasing. The cognitive sensitivity is thus more related to high-level decisional processes about intentional information.

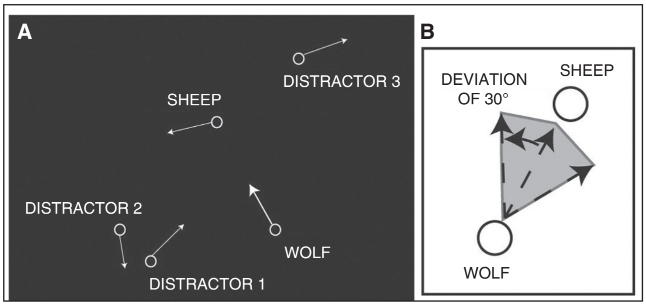

Fig. 1: (A) Screenshot of an animation. Labels and arrows were not present in the actual display. **(B)** Illustration of a 30° chasing efficiency.

Statistical analysis

We compared groups' characteristics using the Student *t* test or χ^2 tests when appropriate. A repeated-measures ANOVA was run on gain of smooth pursuit with group (patient v. control) as a between-subjects factor. Two repeated-measures ANOVAs were run on global sensitivity and bias of chasing detection with chasing (present v. absent) and difficulty (0°, 30° and 60° of chasing efficiency) as within-subjects factors and group as a between-subjects factor. Two repeated-measures ANOVAs were run on stray looking rate and barycentre looking rates with group as a between-subjects factor. Finally, a repeated-measures ANOVA was run on chasing detection sensitivity with processing stage (ocular v. cognitive) and difficulty as within-subjects factors and group as a between-subjects factor.

Results

Participants

Twenty-nine individuals with schizophrenia (n = 27) or schizoaffective disorder (n = 2) and 29 healthy controls participated in this study. All participants had normal or corrected-to-normal vision. At the time of testing, all patients were taking antipsychotics. Groups' characteristics are shown in Table 1. Individuals with schizophrenia or schizoaffective disorder had marginally lower general intelligence and were matched with controls on all other variables.

Patients show normal smooth pursuit ability

There was no significant group effect ($F_{1,56}$ = 0.1, p = 0.81). Patients had a mean gain of 0.834 ± 0.061 and controls had a mean gain of 0.83 ± 0.057.

Patients are overall less sensitive to chasing

Both groups showed very low nonresponse rates (mean for patients: 0.1% ± 0.5%; mean for controls: 0.6% ± 1.8%), and the group difference was not significant ($F_{1,56}$ = 1.6, p = 0.22).

For the sensitivity analysis, the group effect ($F_{1,56}$ = 5.6, p = 0.022) and the difficulty effect ($F_{2,114}$ = 38.9, p < 0.001) were significant. Sensitivity decreased with difficulty in both groups and was higher in controls than in patients. The interaction between group and difficulty was not significant ($F_{2,114}$ = 0.2, p = 0.85; Fig. 2A).

For the bias analysis, the difficulty effect was significant ($F_{2,114}$ = 38.9, p < 0.001). The tendency to give a chasing-absent response increased with difficulty. Neither group ($F_{1,56}$ = 0.47, p = 0.49) nor the interaction between group and difficulty were significant ($F_{2,114}$ = 1.5, p = 0.22; Fig. 2B), showing that patients did not differ from controls in terms of response bias.

Patients have a different looking strategy

There was no significant group difference for the stray looking rate ($F_{1,55}$ = 1, p = 0.33), showing that patients paid as much attention to the stimuli as controls. However, patients had a greater barycentre looking rate than controls ($F_{1,55}$ = 9, p = 0.004), showing a different looking strategy (Fig. 3).

Patients show a global decrease in cognitive and ocular sensitivities

We first ran preliminary analyses to assess differences in agent preference index between patients and controls, the association between the agent preference index and the presence of chasing and the association between forced-choice responses and the agent preference index (see the Appendix).

Table 1: Characteristics of study participants

	Group; mean ± SD*			
Variable	Schizophrenia n = 29	Control n = 29	Statistic	p value
Sex, male/female	21/8	19/10	χ^2 = 0.1	0.78
Visual correction, CL/G	1/12	3/9	χ^2 = 0‡	> 0.99
Age, yr	39 ± 12.5	40.7 ± 13.5	t_{56} = 0.5	0.63
Educational level, yr	12 ± 2.3	12.4 ± 1.5	t_{56} = 0.9	0.39
Estimated general intelligence†	8.3 ± 2.1	9.3 ± 2.1	t_{56} = 1.8	0.08
Illness duration, yr	18 ± 11.1	—		
Hospitalizations duration, mo	16.5 ± 19.3	—		
Haloperidol equivalents, mg/24 h	11.7 ± 8.6	—		
PANSS total	90.6 ± 12	—		
PANSS positive	21.8 ± 4	—		
PANSS negative	24.3 ± 4.9	—		
PANSS general symptoms	44.5 ± 6.8	—		

CL = contact lenses; G = glasses; PANSS = Positive and Negative Syndrome Scale; SD = standard deviation.
*Unless otherwise indicated.
†Mean scaled scores, from 1 to 19. Wechsler intelligence scale scores have a mean of 10 and SD of 3 in the general population.
‡For the χ^2 test, contact lenses and glasses were counted as 1 category owing to small sample size.

We then turned to the analysis of ocular and cognitive chasing detection sensitivities.

The repeated-measures ANOVA on ocular and cognitive sensitivities showed significant effects of group ($F_{1,55}$ = 6.7, p = 0.012) and difficulty ($F_{2,112}$ = 25.4, p < 0.001) and a marginal effect of processing stage ($F_{1,56}$ = 3.1, p = 0.08), but no significant interaction between group and processing stage ($F_{1,56}$ = 2.1, p = 0.15). Thus, patients showed lower sensitivity than controls at both processing stages (Fig. 4).

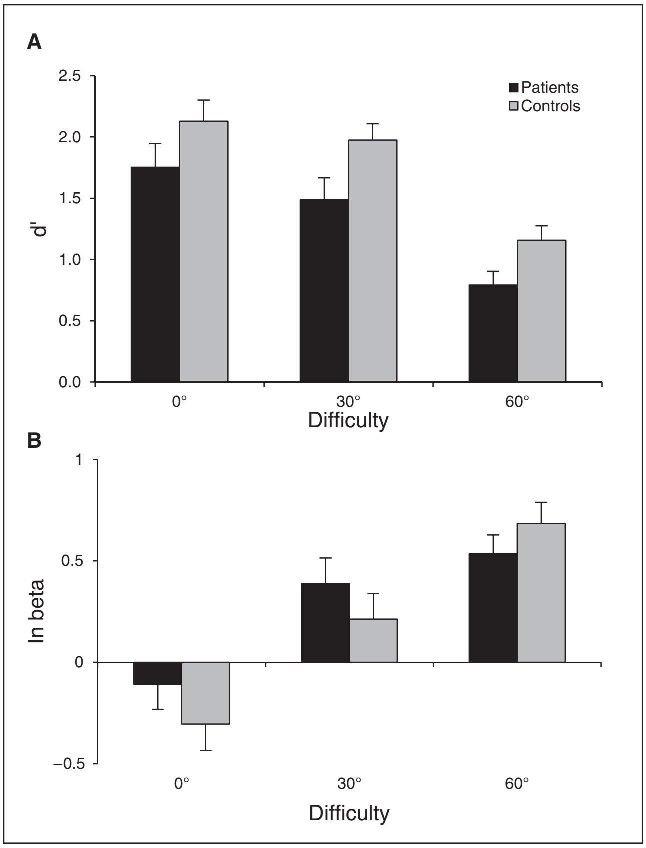

Fig. 2: (A) Mean global sensitivity and **(B)** bias computed from explicit forced-choice responses. Error bars represent standard errors of the mean.

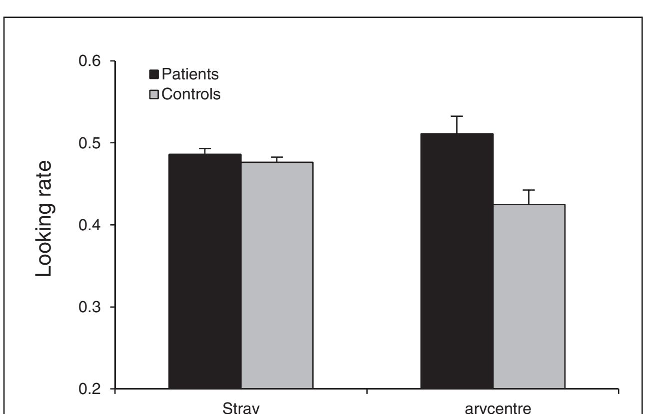

Fig. 3: Mean stray- and barycentre-looking rates. Error bars represent standard errors of the mean.

Reduced ocular, but not cognitive, sensitivity is explained by looking strategy

We explored to what extent low-level oculomotor and general cognitive factors explained group differences in ocular and cognitive sensitivities between patients and controls. A schematic summary of the working model on which the following analyses are based is presented in Figure 5. We computed a simultaneous linear regression on ocular sensitivity with difficulty, maintenance gain, stray looking rate, barycentre looking rate, estimated IQ and group as independent variables (Table 2). The effect of difficulty for the 60° versus 30° contrast (t_{110} = –3.8, p < 0.001) and the effect of barycentre looking strategy (t_{110} = –3.1, p = 0.003) were significant after taking into account the effects of all other variables, suggesting that the group difference in ocular sensitivity may be attributable to differences in looking strategy.

We then computed a simultaneous linear regression on cognitive sensitivity, with difficulty, maintenance gain, stray looking rate, barycentre looking rate, estimated IQ, ocular sensitivity and group as independent variables (Table 2). The effects of ocular sensitivity (t_{109} = 9.1, p < 0.001) and group (t_{53} = 2.3, p = 0.023) were significant after taking into account the effects of all other variables. These

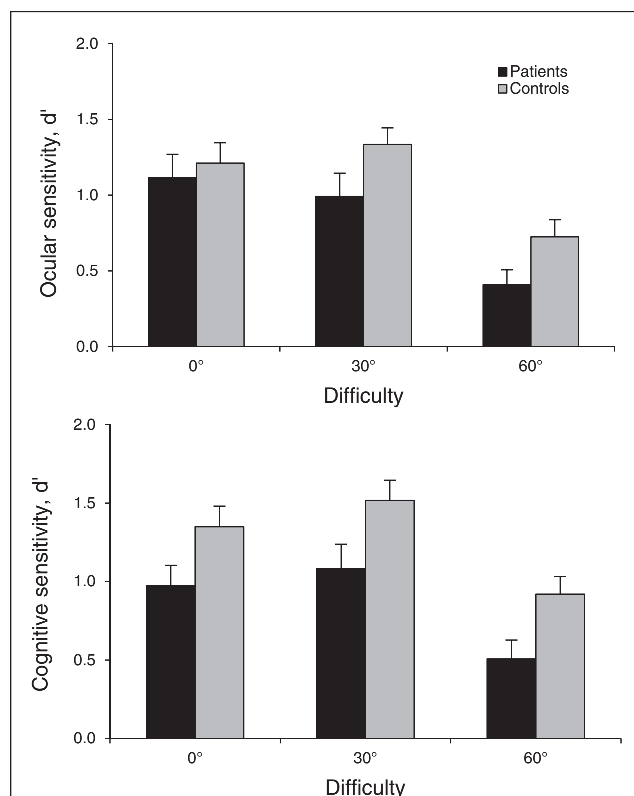

Fig. 4: Mean perceptual and cognitive sensitivities. Error bars represent standard errors of the mean.

results suggest that the group difference in cognitive sensitivity does not reduce to any lower-level or general cognitive factors that we could measure.

Discussion

The main aims of this study were to determine whether individuals with schizophrenia or schizoaffective disorder have a hyper- and/or a hypomentalizing deficit in their detection of intentional motion; whether low-level processes of intentional motion are equally affected as high-level and explicit processes; and to what extent group differences may be explained by differences in smooth pursuit abilities, perceptual exploration strategies or in general cognitive abilities.

We found that patients had on average a lower sensitivity to chasing detection than controls. No difference was found for bias. These results are consistent with hypomentalization (which predicted lower sensitivity) and inconsistent with hypermentalization (which predicted higher bias for chase responses). A potential explanation for this difference could be the effect of antipsychotic medication. However, this seems unlikely given that a marginally significant positive correlation was found between antipsychotic drug dosage and chasing detection sensitivity ($r = 0.35$, $p = 0.06$).

To follow with the lowest levels of processing, no difference was found in smooth pursuit between the 2 groups. This result may seem surprising given that a smooth-pursuit deficit is one of the most replicated psychophysiological abnormalities in schizophrenia.[15] It may be explained by the fact that we matched patients and controls on educational level and IQ, whereas this is often not the case in smooth pursuit studies: O'Driscoll and Callahan[15] published a meta-anlysis

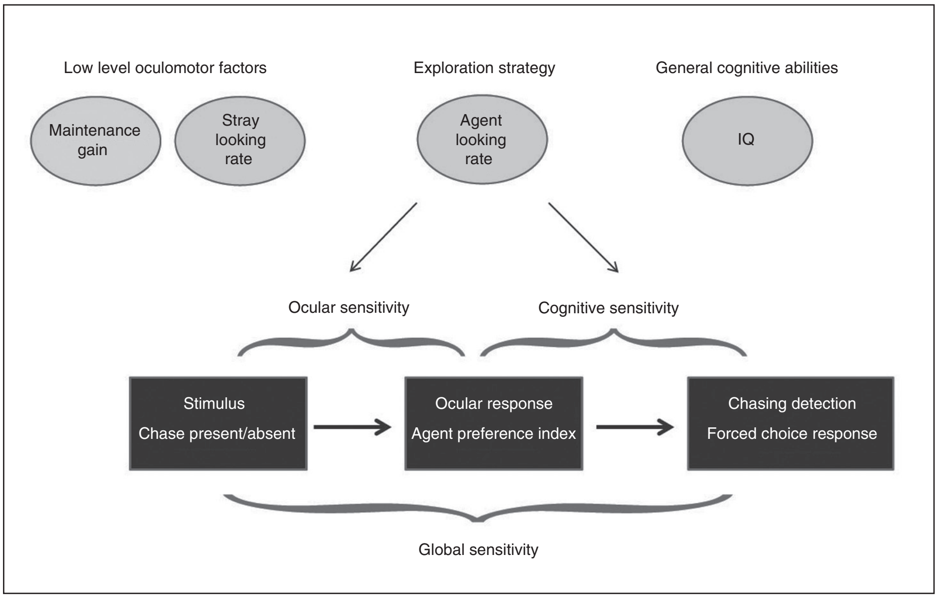

Fig. 5: Working model of chasing detection.

Table 2: Simultaneous linear regression analyses of perceptual and cognitive sensitivities

	Dependent variable					
	Perceptual sensitivity, R^2 = 31.3%			Cognitive sensitivity, R^2 = 51%		
Independent variables	β†	(95% CI)	*p* value	β^2	(95% CI)	*p* value
Chasing efficiency, 0° v. 30°	0.12	(–0.16 to 0.41)	0.38	0.21	(–0.05 to 0.46)	0.10
Chasing efficiency, 60° v. 30°	–0.8	(–1.1 to –0.53)	< 0.001	–0.13	(–0.42 to 0.15)	0.36
General intelligence	0.05	(–0.13 to 0.24)	0.57	0.07	(–0.07 to 0.2)	0.31
Gain of smooth pursuit	–0.02	(–0.21 to 0.17)	0.87	0.08	(–0.05 to 0.22)	0.23
Stray-looking rate	0.0	(–0.18 to 0.19)	0.97	0.04	(–0.1 to 0.18)	0.55
Barycentre-looking strategy	–0.3	(–0.49 to –0.10)	0.003	–0.03	(–0.17 to 0.12)	0.71
Ocular sensitivity				0.58	(0.45 to 0.71)	< 0.001
Group (controls v. patients)	0.1	(–0.3 to 0.5)	0.61	0.33	(0.05 to 0.62)	0.023

CI = confidence interval.
*R^2 coefficient based on likelihood ratio for mixed models.
†Standardized fixed effect coefficients.

of smooth pursuit studies in 2008 and reported that individuals with schizophrenia and controls were matched on IQ or educational levels in only 10 of 59 studies.

Our analysis of looking strategies revealed subtle differences between patients and controls. First, patients allocated as much visual attention as controls to informative locations (agents or barycentre). This indicates that patients didn't show a general decrease in their motivation to perform the task; however, they adopted a more centre looking strategy whereas controls used a more agent looking strategy. Instead of following 1 agent for a certain amount of time (and jumping to another agent until a chase is detected), patients preferentially looked at the barycentre of all agents, thus obtaining an optimal view of the movements of all agents simultaneously. Two alternative explanations can be given to explain this effect. First, it could be a consequence of slightly less agile eye movements due to an impaired oculomotricity in individuals with schizophrenia, although this explanation is not supported by their intact smooth pursuit ability. Second, it may be related to a deficit in visual exploration. It has been consistently reported that individuals with schizophrenia had shorter scanpath lengths and made longer fixations when they were presented with static pictures[26]; thus, the increased barycentre looking strategy might be a consequence of a restricted scanning ability in individuals with schizophrenia. However, several studies have reported that the restricted scanning found in individuals with schizophrenia on passive viewing tasks normalized in active viewing conditions.[27–29] As participants were given a task in the present study, the more centre looking strategy found in individuals with schizophrenia may better reflect a difference in multiple object tracking ability than a restricted scanning ability. Yet another possibility is that their centre looking strategy is a consequence of a decreased ability to detect and/or to represent agents.

A signal detection analysis run on ocular and cognitive chasing detection sensitivities demonstrated a global decrease in patients. The decreased ocular sensitivity revealed that the implicit, early and online detection of chasing was impaired in patients with schizophrenia. Patients' eye movements were less related to the presence of a chase, suggesting that they may have more often produced ocular detections of chasing on chasing-absent trials but less often produced ocular detections of chasing on chasing-present trials. Furthermore, patients' preferred centre looking strategy entirely explained the decreased ocular sensitivity found in individuals with schizophrenia. This association can be interpreted in 2 ways. First, as mentioned above, the shift from an agent looking to a barycentre looking strategy might be a consequence of the decreased ability to detect and/or to represent agents in patients. Alternatively, the patients' decreased ocular sensitivity might be a consequence of their centre looking strategy, through a deficit in their peripheral vision, which has been reported in several studies.[30,31]

The decreased cognitive sensitivity revealed difficulties deciding whether a chase was present or not and/or producing the appropriate response, even when their eye movement patterns reveal that the chasing information had been correctly processed at the visual level. Impairments in decision making have been extensively reported in individuals with schizophrenia on numerous different tasks.[32]

The decreased cognitive sensitivity remained significantly different between groups once differences in terms of visual exploration and general cognitive abilities were taken into account, thus suggesting that difficulties at the high level and explicit cognitive stage of processing remain the most robust impairment underlying the chasing detection deficit in individuals with schizophrenia.

This result may have some implications for the cognitive remediation of intentional motion detection in individuals with schizophrenia: it suggests that a strategy focusing solely on the lower levels of processing (e.g., oriented toward the normalization of eye movements) might be insufficient to compensate for the intentional motion perception deficit in this population. While perceptual stages should not be overlooked, a remediation strategy involving later explicit cognitive stages (interpretation of perceptual input, decision-making and response production) would seem particularly important.

Limitations

Our study has several limitations. One might argue that the distinction between ocular and cognitive sensitivity is artificial because cognitive processes are already involved in the ocular response. Eye movements are indeed under the influence of 2 kinds of processes: early, open-loop and low-level perceptual processes entirely relying on stimulus properties and later closed-loop processes based on a combination of perceptual and higher cognitive factors, such as attention, expectations, reward memory or learning.[33,34] However, eye-tracking still provides a useful insight into early, implicit and online information processes as well as an opportunity to disentangle them from later reflexive and decisional processes. A second limitation comes from the fact that deficits in the perception of nonsocial motion, including detection of coherent motion[35] and speed[36,37] or direction discrimination,[38] have also been demonstrated in individuals with schizophrenia. Further explorations are needed to clarify whether the intentional motion detection deficit demonstrated in this study can be explained by a general deficit in motion perception in individuals with schizophrenia or whether it is more specific to the social domain.

Conclusion

We found that the detection of intentional motion was decreased in patients with schizophrenia and schizoaffective disorder. This deficit was not explained by altered smooth pursuit abilities, and only its low-level and implicit component was explained by differential looking strategies. Most interestingly, we found that the most robust part of this decreased sensitivity to intentional motion was situated at high-level cognitive stages of processing and could not be explained away either by an abnormal ocular behaviour or by general cognitive abilities.

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Competing interests: None declared.

Contributors: All authors designed the study. P. Roux acquired and analyzed the data, which F. Ramus also analyzed. P. Roux and F. Ramus wrote the article, which all authors reviewed and approved for publication.

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Eye-tracking calibration procedure and analysis of eye-tracking accuracy

Before the beginning of each experiment, the eye tracker was set to obtain the best pupil and corneal reflection images for each participant. Another calibration procedure was carried out after the training phase of each experiment. We used the calibration routines of the eye tracker (9 dots routine for the chasing experiment, 3 horizontal dots routine for the smooth pursuit experiment), presenting dots 1 at time in fixed locations on the screen. In the smooth pursuit experiment, a calibration was done before each of the 5 trials. In the chasing experiment, a calibration procedure was done every 18 trials. Before each trial, 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°.

In the remote/head free configuration of EyeLink 1000, no head stabilization was required because the position of the head was independently tracked and head movements were compensated for. However, one might argue that the eye-tracking accuracy may have been lower in individuals with schizophrenia than in controls because of increased involuntary head movements (due for example to extrapyramidal side effects of antipsychotic medication). To ensure that the quality of eye-tracking recording was not different between the groups, we ran repeated measures analyses on postcalibration validation data with group as a between-subjects factor, separately for the chasing and smooth pursuit experiments because the calibration procedure was different. The effect of group was significant neither for the smooth pursuit experiment ($F_{1,56} = 2.2$, $p = 0.14$) nor for the chasing experiment ($F_{1,56} = 0.05$, $p = 0.83$). Thus, eye-tracking was as precise for patients as for controls in both experiments.

To ensure that individuals with schizophrenia didn't blink more often than controls (due, for example, to side effects of antipsychotic medication, such as xerophtalmia), we ran a repeated measures analysis on the number of blinks, with experiment as a within-subjects factor and group as a between-subjects factor. There was a main effect of experiment ($F_{1,56} = 30.9$, $p < 0.001$): there were fewer blinks for chasing (mean: 0.58 ± 0.94) than for smooth pursuit (mean: 4.42° ± 5.78°) because the duration of smooth pursuit trials was greater than that of chasing trials. But there was no main effect of group ($F_{1,55} = 0.8$, $p = 0.39$) and no interaction between group and experiment ($F_{1,56} = 0.2$, $p = 0.67$). Thus, patients didn't blink more often than controls.

Steady-state smooth pursuit task

The visual target was a white circle with a diameter of 0.6° of visual angle on a black background. It moved horizontally with an amplitude of 22° with a constant velocity of 17.13°/s. A trial consisted of 15 traverses in each direction (30 segments per trial) with a pause of 500 ms at each extremities of the screen. Five trials were run for each participant, preceded by a training trial. Eye-tracking data were filtered for artefacts, such as blinks. Horizontal velocity was computed on the 30 segments, starting 400 ms after the onset of the traverse and ending 200 ms before its end. Any ocular sample whose velocity was above 40°/s was considered as a saccade and was consecutively excluded from the analysis. Samples adjacent to these high-velocity portions were also considered as part of a saccade if their velocity was above 20°/s. The gain was computed by dividing the mean velocity of the eye by the mean velocity of the target separately for each of the 28 segments after exclusion of the first 2 segments. Mean gain was computed by averaging the best 75% values of the 28 segments in each of the 5 trials.

Chasing detection paradigm

When viewed from 62 cm, the 5 moving circles had a diameter of 1.2° and were drawn as white outlines with a 0.12° stroke. They moved on a black background (38° × 24°) at a constant speed of 17.4°/s and bounced on the background limits. Each trial lasted 10 seconds. On chasing-present trials, there were

- 3 distractors and 1 sheep that moved in an identical manner. On each frame, an agent had a 9.8% probability of changing its direction within a 120° window.
- 1 circle was the wolf. In the first 100 ms, it moved similarly to the distractors and the sheep. Then, it had a 9.8% probability of changing its direction within a window centred on the position held by the sheep 100 ms earlier, plus or minus the chasing efficiency angle (0°, 30° or 60°).

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At the beginning of a trial, the position of each circle was randomly set with the condition that the wolf and the sheep should be distant by more than 19.2°. Chasing-absent trials were obtained with the same algorithm as chasing-present trials, except that the sheep was removed and replaced by another distractor. This ensured that any difference between the 2 conditions would be due to the contingency between wolf and sheep rather than to the peculiar motion pattern of the wolf.

All participants were trained on 6 trials (chasing-present and chasing-absent trials for each of the 3 degrees of chasing efficiency) with feedback. When participants failed, the trial was replayed. When the failed trial was a chasing-present trial, it was replayed with the wolf drawn in red and the sheep in green. Test trials were presented in a pseudorandom order such that no more than 3 trials with the same expected response were presented consecutively.

Signal detection analysis formulas

Sensitivity: d'= z(H) - z(F)

Bias: $\ln\beta = -1/2\ (z(H)^2 - z(F)^2)$

H is the hit rate, F is the false-alarm rate and z is the inverse function of the normal distribution. Null values of H and F were replaced by 1/2N, with N being the number of trials per participant (78). When H and F were equal to 1, they were replaced by 1-1/2N.

Visual exploration strategies

No eye-tracking data were available for 1 patient owing to a failure in the calibration procedure. At each sample in the eye tracker recording it was determined whether the gaze was located on an agent, on the barycentre of the agents, or elsewhere (stray-looking). Agent-looking was defined by the eye gaze being located within 2.5 times the radius of an agent (hence within a concentric circle of 1.5° radius). Barycentre-looking was defined by the eye gaze being located within 1.5° of the barycentre (mean coordinates) of the 5 agents. Agent- and barycentre-looking are not mutually exclusive. Finally, stray-looking was defined by neither agent- nor barycentre-looking. Stray-looking rates were calculated by dividing the corresponding number of samples by the total number of samples after blink filtration. Agent, barycentre- and stray-looking rates were calculated by dividing the corresponding number of samples by the sum of barycentre-looking and agent-looking samples.

Agent preference index, ocular and cognitive sensitivities

No eye-tracking data were available for 1 patient owing to a failure in the calibration procedure. The eye-tracking samples for which the gaze fell near an agent (when the distance between gaze position and the centre of any agent was below 2.5 times the radius of an agent) were selected from chasing-present and chasing-absent trials. Agent-looking rates were normalized such that the sum of the 5 agents' looking rates was always equal to 1 for each sample, even when participants looked near several agents at the same time. The 5 agents' looking rates were then averaged across all samples, and the standard deviation was computed. In order to dichotomize the ocular responses into detection and nondetection of chasing, the agent preference index of each trial was compared to the median agent preference index across all trials within each participant. When the actual agent preference index was smaller than the median, the trial was coded as a nondetection of chasing; when it was greater, the trial was coded as a detection. Thus, an ocular hit was defined as an ocular detection of chasing on chasing-present trials, while an ocular false-alarm was defined as an ocular detection of chasing on chasing-absent trials. The ocular sensitivity is a d' based on ocular hits and false alarms. Similarly, a cognitive hit was defined as a chasing-present answer when there was an ocular detection of chasing, while a cognitive false-alarm was defined as a chasing-present answer when there was an ocular nondetection of chasing. The cognitive sensitivity is a d' based on cognitive hits and false alarms.

Association between the presence of chasing, the agent preference index and forced-choice responses

A multiple linear regression was run on the agent preference index as dependent variable, with group and chasing (absent v. present) factors as independent variables. It showed no significant effect of group ($F_{1,55} = 0.9$, $p = 0.36$): the agent preference index was similar between schizophrenia and control groups. This suggests that the

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median split analysis used to compute the agent preference index was equally appropriate for both groups. Furthermore, there was a main effect of chasing ($F_{1,55}$ = 252.3, p < 0.001) and a marginal interaction between group and chasing ($F_{1,55}$ = 3.3, p = 0.08): the effect of chasing was greater in controls ($F_{1,28}$ = 243.4, $p < 0.001^{-3}$, R^2 = 0.739) than in patients with schizophrenia ($F_{1,27}$ = 71.1, p < 0.001, R^2 = 0.503). In other words, controls' agent preference index was more sensitive to the chase-absent/present distinction than that of patients.

A multiple logistic regression analysis was run to analyze the association between explicit responses as the dependent variable and the agent preference index and group as independent variables. It showed a significant effect of agent preference index (z = 10.4, p < 0.001) and of group (z = –2, p = 0.046) and a significant interaction between group and the agent preference index (z = 3, p = 0.003). Thus, the probability to give a chasing-present answer increased with the agent preference index (estimated coefficient: 16.2 ± 0.7), and was overall larger in controls than in patients with schizophrenia. Furthermore, the association between chasing detection responses and the agent preference index was weaker in patients with schizophrenia (z = 9.7, p < 0.001, pseudo R^2 = 0.207) than in controls (z = 15.1, p < 0.001, pseudo R^2 = 0.343).

These results thus show that the presence of chasing influences the variability of gaze distribution (as quantified by the agent preference index), which in turns influences forced-choice responses, as illustrated in Figure 5 of the main article. Furthermore, they show that the associations among these 3 variables are weaker in patients with schizophrenia than in controls.