

# 1 Sensorimotor awareness requires intention: Evidence from minuscule eye 2 movements.

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10

## 11 **Abstract**

12 Microsaccades are tiny eye movements that are thought to occur spontaneously and without  
13 awareness but can also be intentionally controlled with high precision. We used these tiny  
14 visual actions to investigate how intention modulates sensorimotor awareness by directly  
15 comparing intended, unintended, and spontaneous microsaccades. In addition, we dissociated  
16 the effects of action intention and the actions' visual consequences on awareness. In 80% of  
17 all trials, we presented a stimulus at high temporal frequency rendering it invisible during stable  
18 fixation. Critically, the stimulus became visible when a microsaccade in the same direction  
19 caused it to slow down on the retina (generated microsaccade condition; 40% of trials) or when  
20 the microsaccades' visual consequence was replayed (replayed microsaccade condition; 40%  
21 of trials). Participants reported whether they perceived the stimulus (visual sensitivity), whether  
22 they believed they had made a microsaccade (microsaccade sensitivity), and their level of  
23 confidence that their eye movement behavior was linked to their perception (causality  
24 assignment). Visual sensitivity was high for both, generated and replayed microsaccades and  
25 comparable for intended, unintended, and spontaneous eye movements. Microsaccade  
26 sensitivity, however, was low for spontaneous microsaccades, but heightened for both intended  
27 and unintended eye movements, showing that the intention to saccade or fixate enhances  
28 awareness of otherwise undetected eye movements. Visual consequences failed to aid eye  
29 movement awareness, and confidence ratings revealed a poor understanding of a causal  
30 relationship between eye movement and sensory consequence. These findings highlight the  
31 functional relevance of intention in sensorimotor awareness at the smallest scale of visual  
32 actions.

33

## 34 **Significance statement**

35 While eye movements are among the most frequent human actions, they are rarely perceived  
36 consciously, despite causing sweeping changes in retinal inputs. Here investigate how  
37 intention can modulate awareness of even the smallest human actions: microsaccades. We  
38 developed a novel paradigm that allowed us to dissociate the role of action intention and an  
39 action's sensory consequence for awareness, two factors that previous research has typically  
40 confounded. Our data provide strong evidence that observers can detect small eye movements  
41 reliably and demonstrates that sensitivity towards microsaccades was neither driven by an eye  
42 movement's motor component nor its visual consequences alone. Instead, we find that  
43 intention opens a gate to sensorimotor awareness, even for actions typically too small to be  
44 perceived.

## 45 Introduction

46 Vision is inherently active (Ahissar & Arieli, 2001; Rolfs, 2015; Rucci et al., 2018; Rucci &  
47 Victor, 2015)—the eyes move incessantly to sample different aspects of the environment over  
48 time. Despite the high frequency of these visual actions and their immediate visual  
49 consequences (Rolfs & Schweitzer, 2022), we appear to have little access to our own past or  
50 ongoing eye movement behavior (Marti et al., 2015; Vő et al., 2016). It thus remains elusive to  
51 what degree we have sensorimotor awareness, or even a sense of agency (Haggard, 2017),  
52 for eye movements at all. Sensorimotor awareness likely hinges on the degree of intended  
53 control over these movements and the distinction between self-generated and externally-  
54 generated sensory signals. But these two factors are inherently difficult to manipulate in any  
55 domain of action control, as one must exactly match intended and unintended movements with  
56 respect to both their kinematics and their sensory consequences. Here, we address this  
57 challenge by capitalizing on microsaccades—minuscule eye movements with reliable  
58 kinematics that occur spontaneously during gaze fixation (Cook et al., 1966; Yarbus, 1967;  
59 Zuber et al., 1965), but can also be controlled (Guzhang et al., 2024; Ko et al., 2010; Poletti et  
60 al., 2020; Shelchikova & Poletti, 2020; Willeke et al., 2019)—to investigate how (1) the intention  
61 to move and (2) the resulting visual consequences modulate sensorimotor awareness for eye  
62 movements.

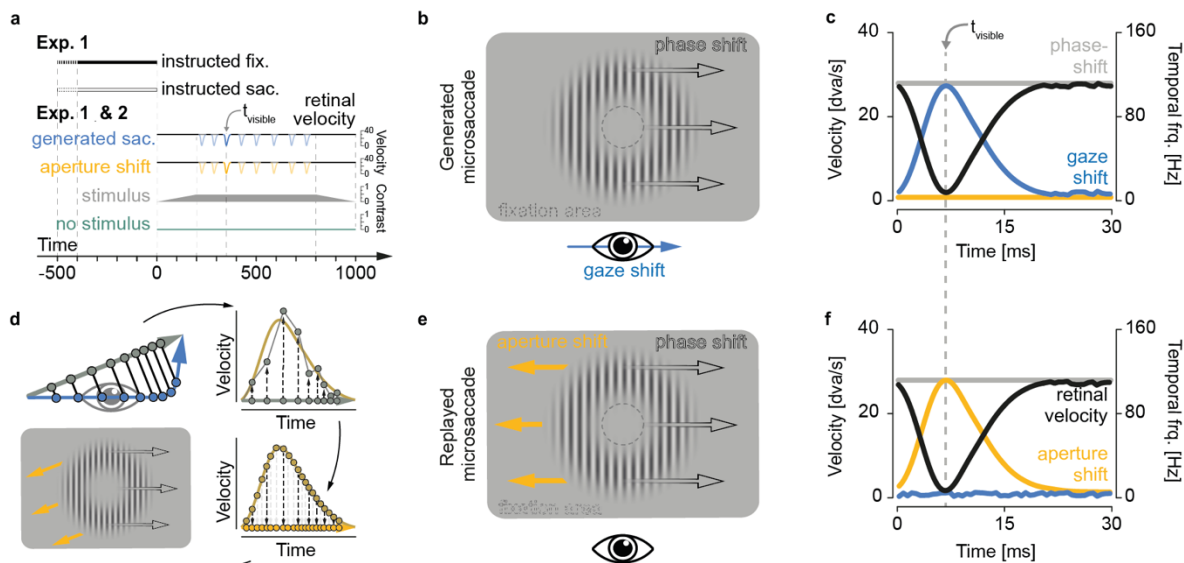
63 Microsaccades are an intriguing oculomotor model for eye movement awareness that  
64 allows us to disentangle these two factors. First, microsaccades frequently occur  
65 spontaneously when observers have the intention to fixate. Given their minuscule size, they are  
66 assumed to escape awareness (Engbert & Kliegl, 2004; Martinez-Conde et al., 2004; Rolfs,  
67 2009; Rosenzweig & Bonneh, 2019). At the same time, observers can intendedly move their  
68 eyes over similarly small amplitudes when guided by visual cues (Ko et al., 2010; Poletti et al.,  
69 2020) or memory alone (Hafed & Goffart, 2020; Willeke et al., 2019). This provides an  
70 experimental handle on the effect of intention on eye movement awareness: By directly  
71 comparing awareness for spontaneous, unintended, and intended microsaccades, we can  
72 assess if the intention to move makes observers more sensitive to self-generated actions.  
73 Second, microsaccades lead to small, rapid displacements of the visual scene on the retina  
74 that are not perceived under normal viewing conditions. Fast flickering (Deubel & Elsner, 1986)  
75 or phase-shifting stimuli (Kelly, 1990), however, render minute eye movements visible by  
76 painting their immediate sensory consequences on the retina. This allows us to carefully  
77 manipulate the presence and magnitude of the visual consequence of the eye movement and  
78 uncover their impact on sensorimotor awareness.

79 So far, only one published report investigated subjective awareness of microsaccades  
80 (Haddad & Steinman, 1973), and they were never compared directly. Haddad and Steinman  
81 (1973) discovered that expert observers can detect spontaneous microsaccades but fail to  
82 recognize their direction. However, it remained unclear if microsaccades were ever falsely  
83 reported in that study. The rate of false alarms, however, is required to determine observers'  
84 sensitivity (Green & Swets, 1966).

85 We developed a paradigm that directly addresses if and how eye movement  
86 awareness depends on the observer's intention to move and the resulting retinal consequence.  
87 To investigate movement intention, we directly compared observers' sensitivity towards having  
88 generated intended, unintended (**Experiment 1**), or spontaneous microsaccades  
89 (**Experiment 2**). In **Experiment 1**, we instructed observers to either execute a small,  
90 deliberate saccade to a memorized target location (Willeke et al., 2019) as soon as the fixation  
91 point (and saccade targets) disappeared (instructed saccade trials; **Fig. 1a**), or to maintain

92 fixation (instructed fixation trials; **Fig. 1a**). Saccades executed in saccade trials were labelled  
 93 *intended microsaccades*. Conversely, saccades executed in fixation trials were labelled  
 94 *unintended microsaccades*. In our second experiment, observers were informed about the  
 95 existence and visual consequences of microsaccades in our paradigm but did not receive  
 96 specific instructions regarding a required eye movement behavior (**Fig. 1a**). Thus, we labelled  
 97 any occurring saccades as *spontaneous microsaccades*.

98 To investigate the role of visual consequence on eye movement awareness, we  
 99 presented a high-temporal frequency stimulus that was invisible during fixation (> 60 Hz, cf.  
 100 Castet & Masson, 2000), but rendered visible when microsaccades with matching kinematics  
 101 briefly stabilized it on the retina (cf. Deubel et al., 1987; Deubel & Elsner, 1986; Kelly, 1990;  
 102 **Fig. 1b/c**). We added a condition in which the stimulus' aperture replayed a previous eye  
 103 movement back to the observer (**Fig. 1d/e/f**), such that the observer could not determine the  
 104 presence of a microsaccade just based on the visual information alone. Finally, we included a  
 105 condition in which stimulus' contrast was set to 0 to compare detection of eye movements that  
 106 did not cause any visual consequence to eye movements that did. For each of observer, we  
 107 determined three types of sensitivity: (1) their visual sensitivity for detecting a brief visual  
 108 stimulus contingent on microsaccades or their replayed sensory consequences (visual  
 109 sensitivity), (2) their ability to report whether they generated a microsaccade (microsaccade  
 110 sensitivity) and its contingency on stimulus presence, and (3) their confidence that their eye  
 111 movement behavior was linked to their perception (causality assignment).  
 112



113 **Figure 1. Experimental protocol and stimulus design.** **a** Procedure in Experiments 1 and 2. Bars (Experiment 1) indicate  
 114 presentation of the fixation dot and saccade target in trials in which either an intended (white) or an unintended microsaccade  
 115 (black) was prompted. Black lines indicate constant retinal velocity of the stimulus, colored sections denote the stimulus being  
 116 slowed down on the retina by a generated (blue) or replayed (yellow) microsaccades. Trapezoid shape depicts contrast modulation  
 117 of the stimulus (grey). We included a stimulus absent condition (green) as an additional control, in which the stimulus contrast  
 118 was set to zero. **b** Stimulus display for generated microsaccades. Gray arrows indicate the direction of the phase shift, blue arrow  
 119 indicates the direction of a microsaccade that leads to a retinal stabilization of the stimulus. **c** Velocity profiles of the phase shift  
 120 (gray line), gaze shift (blue line), aperture shift (yellow line), and retinal velocity (black line) for generated microsaccades. The  
 121 phase shift leads to temporal frequencies >60 Hz and renders the stimulus invisible during fixation. Only if the stimulus is slowed  
 122 down on the retina by a microsaccade, will the combined stimulus velocity drop below the detection threshold. **d** Schematic  
 123 depiction of the steps to generate the aperture motion that replays the retinal consequence of a previous microsaccade  
 124 (clockwise): Projection of sampled gaze position to saccade vector (upper left), fitting of a gamma function to the velocity profile  
 125 along the saccade vector (upper right), recalculation of the gaze positions along the saccade vector based on the fitted velocities  
 126 (lower right), aperture shift in the opposite direction to mirror retinal image displacement (lower left). **e** Stimulus display for replayed  
 127 microsaccades. Gray arrows indicate the direction of the phase shift (same as in b), yellow arrows indicate the direction of an  
 128 aperture shift that replays the retinal consequence of a microsaccade and leads to a comparable retinal stabilization of the  
 129

130 stimulus. **f** Velocity profiles of replayed microsaccades. Colors are same as in **c**. If the stimulus is slowed down on the retina by a  
131 replayed microsaccade (i.e., the aperture shift), will the combined stimulus velocity drop below the detection threshold.

132

## 133 Results

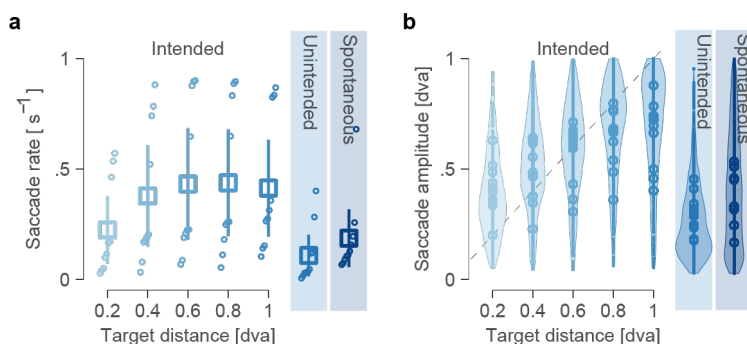
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### 135 *Motor control for microsaccades*

136 The rate of unintended microsaccades was significantly lower than the rate of intended  
137 microsaccades ( $t(9) = 3.49, p = 0.007$ ; unintended: mean =  $0.11 \text{ s}^{-1} \pm 0.09$ ; intended: mean =  
138  $0.38 \text{ s}^{-1} \pm 0.21$ ; **Fig. 2a**), confirming that participants can, to some degree, control  
139 microsaccadic behavior. Target distance (ranging from 0.2 dva to 1 dva) affected the ability to  
140 generate intended microsaccades (one-way rmANOVA:  $F(4,36) = 4.84, p = 0.003$ ; **Fig. 2a**),  
141 with increasing microsaccade rates for larger target distances (0.2 dva:  $0.22 \text{ s}^{-1} \pm 0.15$ ; 0.4 dva:  
142  $0.38 \text{ s}^{-1} \pm 0.23$ ; 0.6 dva:  $0.43 \text{ s}^{-1} \pm 0.25$ ; 0.8 dva:  $0.44 \text{ s}^{-1} \pm 0.24$ ; 1.0 dva:  $0.4 \text{ s}^{-1} \pm 0.22$ ). The rate  
143 for spontaneous microsaccades from **Experiment 2** ( $0.19 \text{ s}^{-1} \pm 0.13$ ; **Fig. 2a**) was in between  
144 those of unintended and intended microsaccades, and not statistically different from either  
145 intended ( $t(15.2) = 1.76, p = 0.098$ ), or unintended ( $t(16.4) = -1.09, p > 0.250$ ) ones (see  
146 section *Saccade rates* in **Supplementary material**).

147 Also, amplitudes of intended microsaccades from **Experiment 1** increased  
148 monotonically (0.2 dva:  $0.41 \pm 0.08$  dva; 0.4 dva:  $0.50 \pm 0.10$  dva; 0.6 dva:  $0.56 \pm 0.10$  dva;  
149 0.8 dva:  $0.64 \pm 0.10$  dva; 1 dva:  $0.66 \pm 0.11$  dva); **Fig. 2b**) with target distance ( $F(4,36) = 28.40,$   
150  $p < 0.001$ ). A linear mixed effects model, fit to the amplitudes of those intended eye  
151 movements, revealed significant positive estimates for all successive difference contrasts (all  
152  $ps < 0.001$ , except 0.8 vs. 1.0 dva:  $t(3238.6) = 1.75, p = 0.079, \text{beta} = 0.02 \pm 0.02$ ). This result  
153 suggests that observers adapted their microsaccade amplitudes to the target distances (for  
154 more information see section *Accuracy and precision of intended microsaccades* in the  
155 **Supplementary material**).

156



157 **Figure 2. Accurate control of microsaccades.** **a** Rates of different types of microsaccades and, for intended microsaccades,  
158 different target distances. Empty circles denote average rates per participant and condition, sorted from lowest to highest by value,  
159 squares indicate group means. Error bars show 95% confidence intervals. **b** Amplitudes of different types of microsaccades and,  
160 for intended microsaccades, different target distances (0.2–1 dva). Empty dots indicate average amplitudes per participant and  
161 target amplitude, violin-plots indicate distribution of all saccade amplitudes and target distances.

162

### 163 *Visual sensitivity to intra-saccadic stimulation*

164 Next, we confirmed that observers were indeed visually insensitive to the high-temporal  
165 frequency stimulus displayed during fixation: In the absence of microsaccades, observers'  
166 sensitivity for detecting the stimulus was not statistically different from 0 (**Exp. 1**:  $d' =$   
167  $0.16 \pm 0.19$ ; **Exp. 2**:  $d' = 0.10 \pm 0.29$ ; **Fig. 3a**). This insensitivity was indistinguishable between  
168 intended ( $d' = 0.13 \pm 0.18$ ) and unintended ( $d' = 0.20 \pm 0.22$ ; **Exp. 1**:  $t(9) = -1.13, p > 0.250$ ) as

169 well as spontaneous microsaccades compared to eye movements from **Experiment 1 (Exp. 1**  
170 **vs 2:**  $t(15.4) = 0.44$ ,  $p > 0.250$ ).

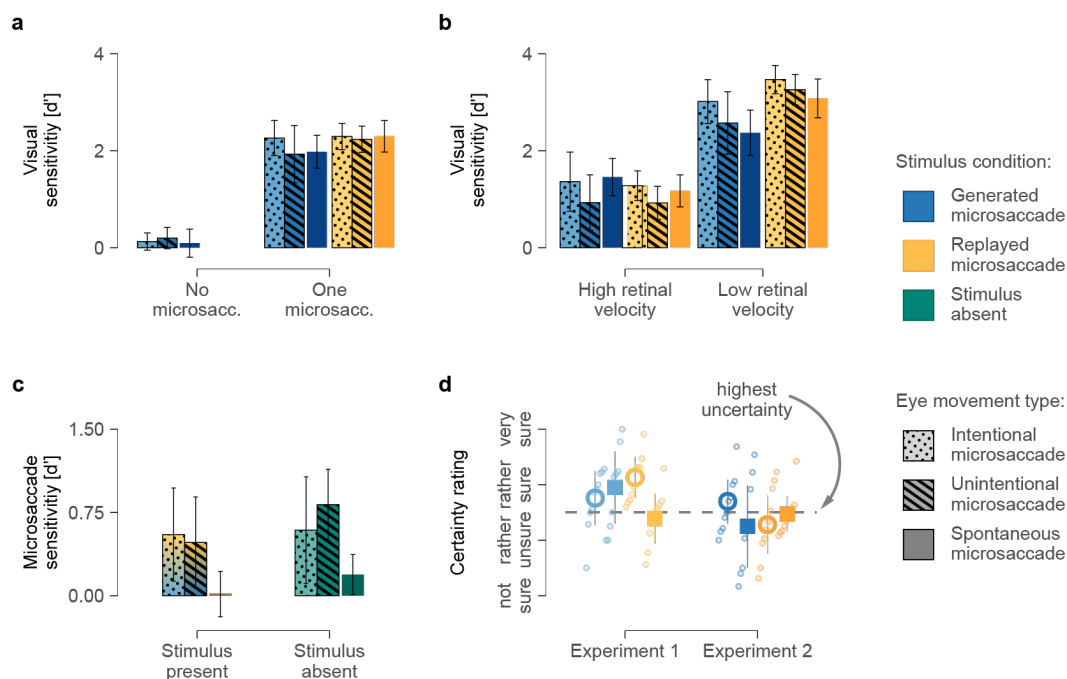
171 Intended and unintended microsaccades ( $d' = 2.10 \pm 0.46$ ) as well as their replayed  
172 retinal consequences ( $d' = 2.27 \pm 0.25$ ), rendered the stimulus highly visible (**Fig. 3a**). A two-  
173 way rmANOVA revealed that the increase in visibility was the same irrespective of stimulus  
174 condition (generated vs. replayed;  $F(1,9) = 1.61$ ,  $p = 0.236$ ) and eye-movement type (intended  
175 vs. unintended;  $F(1,9) = 4.15$ ,  $p = 0.072$ ; interaction:  $F(1,9) = 2.34$ ,  $p = 0.160$ ). In  
176 **Experiment 2**, spontaneous microsaccades, both generated ( $d' = 1.98 \pm 0.34$ ) or replayed ( $d'$   
177  $= 2.30 \pm 0.33$ ), resulted in a similar visual sensitivity (**Fig. 3a**). A mixed-measures ANOVA with  
178 the between-subject factor experiment (**Exp. 1 vs. 2**) and the within-subject factor stimulus  
179 condition (generated vs. replayed) revealed that stimulus sensitivity was not significantly  
180 different between the two experiments ( $F(1,18) = 0.04$ ,  $p > 0.250$ ). A significant main effect of  
181 stimulus condition ( $F(1,18) = 8.87$ ,  $p = 0.008$ ) in the absence of an interaction ( $F(1,18) = 0.84$ ,  
182  $p > 0.250$ ), however, showed that stimulus sensitivity was slightly higher when the sensory  
183 consequences of microsaccades were replayed ( $d' = 2.22 \pm 0.20$ ) rather than generated by an  
184 eye movement ( $d' = 1.98 \pm 0.28$ ).

185 The match between microsaccade kinematics and stimulus parameters markedly  
186 affected visual sensitivities (**Fig. 3b**). Intended and unintended microsaccades from  
187 **Experiment 1** that matched the speed and direction of the high-temporal frequency stimulus—  
188 leading to low retinal velocities within  $\pm 30$  dva/s of the grating's velocity—yielded significantly  
189 higher visual sensitivity ( $d' = 3.08 \pm 0.34$ ) than trials with mismatching parameters ( $d' =$   
190  $1.12 \pm 0.35$ ; **Exp. 1:**  $t(8) = -13.94$ ,  $p < 0.001$ ). A three-way rmANOVA revealed that both retinal  
191 velocity (low vs. high velocity;  $F(1,8) = 194.39$ ,  $p < 0.001$ ) and stimulus condition (generated  
192 vs. replayed;  $F(1,8) = 5.94$ ,  $p = 0.041$ ) affected visibility; sensitivity was higher for low  
193 compared to high retinal velocities, and for replayed compared to generated microsaccades.  
194 A significant interaction between retinal velocity and stimulus condition ( $F(1,8) = 7.08$ ,  $p =$   
195  $0.029$ ) highlighted that the impact of retinal velocity on visibility was larger for replayed than  
196 generated microsaccades. Lastly, a significant main effect of eye movement type ( $F(1,8) =$   
197  $5.87$ ,  $p = 0.042$ ) revealed that stimulus visibility was also slightly higher for intended ( $d' =$   
198  $2.28 \pm 0.30$ ) compared to unintended microsaccades ( $d' = 1.92 \pm 0.39$ )—potentially due to the  
199 overall lower size and peak velocity of unintended microsaccades (see section *Parameters of*  
200 *different eye movement types* in **Supplementary material**). All remaining interactions were  
201 not significant (all  $ps > 0.250$ ).

202 Spontaneous microsaccades in **Experiment 2** showed a similar benefit in visual  
203 sensitivity for low ( $d' = 2.73 \pm 0.41$ ) over high ( $d' = 1.32 \pm 0.33$ ) retinal velocities (**Exp. 2:**  $t(9) =$   
204  $-8.28$ ,  $p < 0.001$ ; **Fig. 3b**). In a three-way mixed-measure ANOVA with experiment as the  
205 between-subject factor, and stimulus condition as well as retinal velocity as within-subject  
206 factors, the main effect of retinal velocity was highly significant ( $F(1,17) = 226.33$ ,  $p < 0.001$ )  
207 while the main effect of experiment was not ( $F(1,17) = 0.17$ ,  $p > 0.250$ ). Thus, the increase in  
208 visual sensitivity for low compared to high retinal velocities was consistent for all three types  
209 of eye movements. Similarly, stimulus condition (generated vs. replayed) affected visual  
210 sensitivity ( $F(1,17) = 11.93$ ,  $p = 0.003$ ) and interacted with retinal velocity ( $F(1,17) = 33.07$ ,  $p$   
211  $< 0.001$ ), implying that the general advantage for low compared to high retinal velocities is  
212 larger for the replayed than the generated stimulus condition. Finally, a significant interaction  
213 between the experiment and the retinal velocity ( $F(1,17) = 5.93$ ,  $p = 0.026$ ) indicated that the  
214 gain in visibility for low compared to high retinal velocities is smaller for spontaneous than for

215 intended and unintended microsaccades. No other interactions were significant (all  $ps >$   
 216 0.191).

217 The analysis of visual sensitivity confirmed that our high-temporal frequency stimulus  
 218 was visible only during the presence of generated or replayed microsaccades, with only small  
 219 variations between instruction and, thus, eye-movement types. Sensitivity increased when  
 220 stimulus and microsaccade parameters matched, confirming that gaze-contingent retinal  
 221 stabilization determined the visibility during the microsaccade. Additionally, observers were  
 222 slightly more sensitive towards replayed compared to generated microsaccades. We attribute  
 223 this difference to an overestimation of saccade peak velocity in video-based eye tracking (cf.  
 224 Schweitzer & Rolfs, 2022), which would yield a small but systematic discrepancy in the  
 225 effective retinal velocity between the generated and replayed condition. In addition, saccadic  
 226 suppression (i.e., the decrease in visual sensitivity during eye movements) may have reduced  
 227 visual sensitivity as well (Hafed & Krauzlis, 2010; Zuber & Stark, 1966).  
 228



229 **Figure 3. Visual and microsaccade sensitivity.** **a** Visual sensitivity as a function of microsaccade generation for different  
 230 stimulus conditions and eye movement types. **b** Visual sensitivity as a function of retinal velocity (in low-velocity trials, the  
 231 saccade's peak velocity was within  $\pm 30$  dva/s of the grating's velocity; in high-velocity trials, it was outside that range).  
 232 **c** Microsaccade sensitivity as a function of stimulus presence and eye-movement type. **d** Certainty of judgment about the causal  
 233 relationship between stimulus percept and eye movement for the two experiments. Error bars indicate 95% confidence intervals.

### 234 *Microsaccade sensitivity*

235 We next examined how sensitive observers were in detecting their own eye movements and  
 236 how this microsaccade sensitivity depended on the absence vs. presence of a visual stimulus.  
 237 In **Experiment 1**, observers were moderately sensitive to both intended ( $d' = 0.57 \pm 0.43$ ), and  
 238 unintended microsaccades ( $d' = 0.65 \pm 0.33$ ; **Fig. 3c**). A two-way rmANOVA revealed that  
 239 sensitivity was comparable between the two different types of eye movements (intended vs.  
 240 unintended;  $F(1,9) = 0.11$ ,  $p > 0.250$ ). The presence of a visual stimulus significantly  
 241 decreased microsaccade sensitivity (present vs. absent;  $F(1,9) = 5.40$ ,  $p = 0.045$ ). Observers  
 242 were more sensitive to their own microsaccades in trials in which no stimulus was present ( $d'$   
 243  $= 0.71 \pm 0.28$ ) as compared to trials with a stimulus ( $d' = 0.51 \pm 0.30$ ; **Fig. 3c**). The interaction of

244 eye-movement type and stimulus presence, on the other hand, was not significant ( $F(1,9) =$   
245  $2.64, p = 0.139$ ).

246 Next, we compared the results for intended and unintended microsaccades to  
247 spontaneous eye movements from **Experiment 2**. In line with our predictions, we found  
248 microsaccade sensitivity to be much lower for spontaneous microsaccades both in stimulus  
249 absent ( $d' = 0.19 \pm 0.18$ ) and stimulus present trials ( $d' = 0.02 \pm 0.21$ ; **Fig. 3c**). Indeed, in stimulus  
250 present trials, microsaccade sensitivity for spontaneous microsaccades was indistinguishable  
251 from 0. A two-way mixed-measures ANOVA that assessed microsaccade sensitivity based on  
252 stimulus presentation as a within-subject factor, and experiment as a between-subject factor  
253 revealed main effects of stimulus presentation (absent vs. present;  $F(1,18) = 8.31, p = 0.010$ )  
254 and experiment ( $F(1,18) = 12.91, p = 0.002$ ), with no interaction ( $F(1,18) = 0.02, p > 0.250$ ).  
255 Thus, stimulus-absent trials led to slightly higher microsaccade sensitivity in both experiments,  
256 and microsaccade sensitivity was lower for spontaneous compared to intended and  
257 unintended microsaccades.

258 In summary, observers were just as sensitive to unintended microsaccades during  
259 instructed fixation as to intended microsaccades following an instruction to move the eyes. In  
260 contrast, spontaneous microsaccades typically escaped awareness. Indeed, the subjective  
261 microsaccade-contingent change in stimulus visibility did not enhance microsaccade  
262 sensitivity (see section *Microsaccade sensitivity as a function of stimulus perception* in  
263 **Supplementary Material**). Our data instead support the opposite conclusion: the presence of  
264 a visual stimulus had a detrimental effect on microsaccade sensitivity.  
265

#### 266 *Causal assignment: Relating eye movements to their consequences.*

267 We investigated whether observers were able to detect if their own eye movements caused  
268 the stimulus to become visible. We predicted that, if microsaccades were made intendedly and  
269 consciously (and if observers understood that the stimulus became visible because of the  
270 microsaccade), observers should be confident that their eye movements caused the brief  
271 change in stimulus visibility. In other words, certainty about the causal link between eye  
272 movement and stimulus visibility should be a function of sensorimotor awareness of the eye  
273 movement and, thus, higher when the generation of an eye movement was correctly detected.  
274 Due to the lack of trials in which observers correctly detected unintended microsaccades that  
275 rendered the stimulus visible, we collapsed data for intended and unintended eye movements.  
276

277 Focusing on **Experiment 1** first, we found that the reported levels of certainty were  
278 close to the scale's mid-point (i.e., the highest level of uncertainty, 0; **Fig. 3d**) irrespective of  
279 whether the microsaccade was generated ( $0.30 \pm 0.41$ ) or replayed ( $0.22 \pm 0.32$ ). Observers did,  
280 however, show a slightly higher certainty for correct causality assignments ( $0.39 \pm 0.31$ )  
281 compared to when causality was assigned incorrectly ( $0.13 \pm 0.40$ ; **Fig. 3d**), and a two-way  
282 rmANOVA confirmed the significance of this difference ( $F(1,8) = 8.96, p = 0.017$ ). While the  
283 difference between the two stimulus conditions remained insignificant (generated vs replayed:  
284  $F(1,8) = 0.47, p > 0.250$ ), a significant interaction ( $F(1,8) = 5.37, p = 0.049$ ) indicated a higher  
285 certainty for correct (over incorrect) assignments only for replayed eye movements  
286 ( $0.72 \pm 0.36$ ), not for generated ones ( $-0.20 \pm 0.61$ ).

287 In **Experiment 2**, we observed comparable albeit slightly lower levels of certainty for  
288 generated ( $-0.05 \pm 0.42$ ) and replayed spontaneous microsaccades ( $-0.09 \pm 0.34$ ; **Fig. 3d**). Unlike  
289 for **Experiment 1**, observers were not more confident in assigning causality correctly,  
290 compared to incorrectly ( $t(8) = 2.19, p = 0.060$ ; correct:  $0.03 \pm 0.34$ ; incorrect:  $-0.17 \pm 0.43$ ;

290 **Fig. 3d**), and a two-way rmANOVA showed neither factor nor their interaction to be significant  
291 (all  $ps > 0.06$ ).

292 In summary, observers' reports suggested a very limited understanding of the  
293 relationship between eye movement and the stimulus on a trial-by-trial bases. Notably, we  
294 observed an increase in certainty when participants were presented with replayed eye  
295 movements from the first experiment. This increase in certainty implies that observers were  
296 more confident about the absence than the presence of a link between the stimulus and the  
297 eye movement—and only when they were sensitive to their eye movements at all.

298

## 299 **Discussion**

300

### 301 *The role of intention for sensorimotor awareness*

302 We investigated how action intention and an action's visual consequence affect sensorimotor  
303 awareness in human observers. We revealed that action intention enhances sensorimotor  
304 awareness even for movements that are typically too small to be perceived: Observers were  
305 significantly more sensitive to their microsaccades when they intended to make or avoid them  
306 compared to when such microsaccades occurred spontaneously (**Fig. 3c**). Our findings  
307 demonstrate that microsaccades, while phenomenally thin (Clark et al., 2013; Haggard, 2017)  
308 and prone to escape awareness when generated spontaneously (i.e., in the absence of an  
309 intention), can be recognized in principle, and at a level comparable to intended  
310 microsaccades. Importantly, an action's sensory consequence did not lead to a similar  
311 increase in saccade sensitivity, therefore pointing towards action intention as the main factor  
312 for sensorimotor awareness.

313 In our study, we examined the role of movement intention by presenting instructions  
314 in the beginning of each trial, prompting observers' intentions to either generate or suppress a  
315 microsaccade (**Exp. 1**). In a second experiment, we repeated the procedure but without  
316 providing explicit instructions to the observers (**Exp. 2**). The difference in sensitivity between  
317 intended (**Exp. 1**) and spontaneous microsaccades (**Exp. 2**) clearly demonstrates an effect of  
318 intention. Interestingly, the parameters of spontaneous and unintended microsaccades were  
319 similar in our experiments (see **Fig S2**), and the degree of sensorimotor awareness is not a  
320 function of movement parameters alone (e.g., amplitude). Taken together, our data caution  
321 against the classification of saccadic eye movements according to a system of distinct types  
322 based on fixed parameters (e.g., amplitude, duration, or latency) or levels of conscious  
323 processing: Our observers were sensitive to minuscule eye movements—irrespective of  
324 whether they were planned (like intended microsaccades, **Exp. 1**) or unplanned (like the  
325 unintended microsaccades, **Exp. 1**). However, in the absence of an intention, saccades of  
326 similar size, peak velocity, duration, and latency (i.e., spontaneous microsaccades from  
327 **Exp. 2**) routinely escaped conscious detection. Instead of a rigid typology of saccadic activity,  
328 our data support the idea of an oculomotor continuum along which saccades are generated  
329 (Hafed, 2011; Martinez-Conde et al., 2013; Rolfs et al., 2008; Zuber et al., 1965). Sensorimotor  
330 awareness of miniscule motor acts is, in line with this view, not pre-determined by the type of  
331 motor act, but by additional factors—most evidently, action intention.

332

### 333 *Motor control for minuscule eye movements*

334 Generating instructed microsaccades in the absence of visual cues becomes more difficult the  
335 smaller the required amplitude is: We found lower saccade rates and reduced accuracy for  
336 smaller microsaccades which indicated that observers frequently overshoot particularly small



337 target distances (i.e., 0.2 and 0.4 dva; **Fig. 2a** and **Fig. S1a**). Despite that challenge, our data  
338 demonstrate that observers can generate small eye movements reliably—even in the absence  
339 of a foveated visual anchor: Microsaccades were more likely following an instruction to make  
340 a microsaccade and microsaccade amplitudes scaled with target distance. Successful  
341 execution of intended microsaccades increased with target distance, suggesting a graded  
342 control over minute eye movements as a function of saccade amplitude (cf. Willeke et al.,  
343 2019, 2022; see **Fig. 2b**). For trials in which observers were instructed to fixate, we revealed  
344 fewer and smaller microsaccades indicating that these eye movements were generated  
345 despite the intention to fixate. Their average latency also more closely resembled that of  
346 spontaneous microsaccades (**Fig. S2d**), indicating that unintended saccades are not a type of  
347 goal-directed saccade but rather saccadic intrusions (cf. Abadi & Gowen, 2004). Taken  
348 together, these results indicate that our observers exerted a high level of conscious control  
349 over their eye movement generation. But this control is not perfect: The small number of  
350 unintended microsaccades (**Fig. 2a**) suggests that some level of involuntary eye movement  
351 activity cannot be controlled—even when participants are explicitly instructed to do so.

352 The data provided by our two experiments is partially in line with previous findings  
353 claiming that expert observers can detect spontaneous microsaccades (Haddad & Steinman,  
354 1973). Observers in our study showed no sensitivity towards spontaneous microsaccades but  
355 exhibited an increased sensitivity towards their saccades of the same size occurring when  
356 instructed to fixate (**Fig. 3c**). Assuming the expert observers in Haddad's and Steinman's  
357 original study received a similarly explicit instruction to fixate, we can assume a similarly  
358 heightened sensitivity towards unintended small eye movements as exhibited by our  
359 participants. Nevertheless, we want to offer an alternative interpretation of our respective  
360 results, which would accommodate that Haddad and Steinman genuinely measured the  
361 detection of spontaneous microsaccades. We find that detection (i.e., hit rates) of spontaneous  
362 microsaccades is significantly different from zero, when collapsing over all stimulus conditions  
363 and stimulus perception. At the same time, our observers exhibited a comparable increase in  
364 false alarm rates for spontaneous microsaccades (again irrespective of stimulus condition or  
365 perception; see section *Microsaccade (mis-) detection based on stimulus condition and*  
366 *perceptual report* in the **Supplementary material** for the extended analysis of hits and false  
367 alarms), rendering observer sensitivity ( $d'$ ) towards spontaneous microsaccades not  
368 significantly different from zero (**Fig. 3c**). By focusing on hit rates only, Haddad and Steinman  
369 may have inadvertently misconstrued their reports that minuscule eye movements were  
370 generated (when indeed they were) as sensitivity towards microsaccades. Their observer's  
371 inability to report the direction of the generated microsaccades can be seen as support for this  
372 interpretation of their data.

373  
374 *Role of an action's visual consequences for sensorimotor awareness*

375 To investigate how an action's visual consequence affects observers' awareness of the  
376 underlying eye movement, we determined microsaccade sensitivity as a function of stimulus  
377 presence vs. absence. Interestingly, we found that observers were slightly more sensitive to  
378 their eye movements in trials in which the stimulus was absent rather than present (see  
379 **Fig. 3b**), suggesting that vision may have a detrimental effect on eye movement awareness.  
380 To examine this result more closely and explain a seemingly complex set of data, we directly  
381 compared hit and false alarm rates for microsaccades depending on eye movement type,  
382 stimulus condition, and perceptual reports (see section *Microsaccade (mis-) detection based*  
383 *on stimulus condition and perceptual report* in the **Supplementary material**).

384 We found higher hit rates in trials in which participants reported having perceived the  
385 stimulus compared to trials in which participants reported not having perceived it, suggesting  
386 that detection of small eye movements is heightened following a change in the visual input.  
387 Similar detection rates for replayed and generated microsaccades on the other hand suggest  
388 that a match between the visual consequence and the eye movement does not have to be  
389 perfect for observers to conclude that an eye movement has occurred. While this ostensibly  
390 counters our initial impression and instead suggests eye movement awareness benefits from  
391 the display of visual consequences, turning to false alarms levels this impression: We found  
392 that observers reported the erroneous belief to have generated a microsaccade significantly  
393 more often when a replayed eye movement was perceived by the observer compared to when  
394 it was not (**Fig. S4**). The increase in false alarms was comparable to the increasing hit rates  
395 and a re-analysis of microsaccade sensitivity based on stimulus perception (rather than  
396 presentation) revealed no significant difference between trials in which observers reported  
397 having perceived the stimulus compared to trials in which observers reported having perceived  
398 no stimulus (**Fig. S3**). Our findings thus demonstrate that while visual events strongly affect an  
399 observers' beliefs about their eye movements, their effect on eye movement awareness are  
400 surprisingly limited.

401 However, this limited effect on awareness may well be an effect of our paradigm: To  
402 reveal how eye movement awareness was affected by intention, our paradigm decouples the  
403 presence of an eye movement and its visual consequences, as eye movements were neither  
404 necessary (cf. replayed microsaccades) nor sufficient (cf. no-stimulus condition) for seeing the  
405 stimulus. Seeing the stimulus, in turn, bore equally little information about eye movement  
406 generation: The stimulus was rendered visible in the absence of an eye movement when a  
407 visual consequence was replayed and the stimulus remained invisible irrespective of  
408 microsaccade generation in stimulus-absent trials. Relying on stimulus perception was,  
409 therefore, a poor strategy to try and gauge eye movement generation in the context of our  
410 paradigm. In everyday life, however, observers experience their eye movements  
411 predominantly as (highly predictable) changes in what we look at, arguably a visual change.  
412 The over-reliance of our participants on stimulus perception to estimate saccade generation  
413 (as evidenced by the high number of false alarms following stimulus perception for all but  
414 unintended microsaccades; cf. **Fig. S4**) indicates that our beliefs about eye movement  
415 generation critically relies on vision.

416 Lastly, why do we find a higher microsaccade sensitivity in stimulus absent compared  
417 to stimulus present trials? We argue that this is a combined effect of the observer's tendency  
418 to over-estimate eye movement generation when they perceived the stimulus (**Fig. S4**) and  
419 the slightly higher stimulus sensitivity in replay condition trials (**Fig. 3a/b**). A higher visibility of  
420 the stimulus led to marginally higher false alarm rates that—together with comparable hit rates  
421 between stimulus conditions—led to a slightly lower sensitivity in stimulus present trials  
422 (**Fig. 3c**).

423 Taken together, our data support that visual consequences of eye movements are  
424 relevant for sensorimotor awareness of microsaccades: In a situation in which a minuscule eye  
425 movement is itself not very salient, human observers tend to use visual information to try and  
426 estimate if an eye movement was generated. While using vision would be a sound strategy  
427 under natural viewing conditions, where the immediate visual consequences of an eye  
428 movement are rarely matched by external visual events, our paradigm limited the utility of this  
429 approach: By adding a condition in which visual consequences of a saccade was replayed  
430 back to the observer, we decoupled eye movements and their visual consequences to reveal,

431 for the first time, that movement intention is an important driver of sensorimotor awareness for  
432 minuscule eye movements.

433

#### 434 *Causal assignment*

435 Finally, we investigated if participants could relate their eye movements to stimulus perception  
436 after experimentally controlling for an action's visual consequence. More specifically, by  
437 replaying the visual consequences of an eye movement back to the observer, stimulus visibility  
438 could not be used to infer the presence of an eye movement. The present experiments suggest  
439 that observers were unable to develop even a shallow understanding of how their eye  
440 movements related to seeing the stimulus. Observer's average confidence ratings remained  
441 close to the scale's midpoint (the point of highest uncertainty)—especially for eye movements  
442 generated in **Experiment 2 (Fig. 3d)**. Additionally, microsaccade sensitivity was overall low,  
443 suggesting that participants had limited information about their eye movement to infer how it  
444 affected stimulus visibility (**Fig. 3c**). If anything, our data suggests that participants tried to  
445 assign causality by estimating how much they lacked a sense of control over stimulus visibility.  
446 Our results indicate that observers were able to detect the absence of a causal relationship  
447 while they struggled to correctly determine when an eye movement caused the stimulus  
448 percept: In **Experiment 1**, certainty was highest when participants reported that they had *not*  
449 caused the stimulus to become visible, and we replayed a previous eye movement back to  
450 them (**Fig. 3d**). Fittingly, in trials with similarly replayed eye movements, observers were least  
451 certain when expressing the (incorrect) belief that their own microsaccade allowed for stimulus  
452 detection. In contrast, when a generated microsaccade rendered the stimulus visible, certainty  
453 ratings were not statistically different for correct and incorrect causal assignments. Observers  
454 expressed comparable levels of certainty when (correctly) claiming that their eye movement  
455 allowed for stimulus detection and when expressing the (incorrect) belief that the change  
456 stimulus visibility was not due to a microsaccade (**Fig. 3d**).

457 While we already mentioned low microsaccade sensitivity as one potential  
458 explanation, a second, equally interesting explanation can be found in the paradigm itself. We  
459 fundamentally broke how eye movements naturally relate to changes in retinal inputs: We  
460 presented a stimulus that is perceived during a saccade while the pre- and post-saccadic  
461 retinal images were largely identical. This contrasts with natural situations, in which the retinal  
462 input changes drastically across saccades. Replayed eye movements, on the other hand, were  
463 purely visual events—and our observers' task, hence, much more natural. In other words, by  
464 decoupling eye movements and their visual consequences, our paradigm allowed to examine  
465 the role of intention shapes sensorimotor awareness in the active observer. However, by  
466 deviating from how eye movements and their perceptual consequences are linked in natural  
467 viewing, we obscured the relationship between a microsaccade and stimulus perception. This  
468 hindered observers' understanding of how their eye movements influenced stimulus visibility,  
469 explaining observers' low certainty when attributing stimulus visibility to their own eye  
470 movements. Because replaying the retinal consequences of a previous eye movement was a  
471 purely visual event (that did not break with natural viewing in the same way), observers'  
472 certainty was much higher when correctly asserting that the stimulus became visible despite  
473 the absence of a microsaccade.

474

#### 475 *Theoretical implications*

476 To summarize, we found no evidence that the parameters of eye movements affected the  
477 degree to which observer were aware of them, as miniscule saccades of similar amplitude,

478 peak velocity, and duration could either be detected (i.e., intended and unintended  
479 microsaccades) or not (i.e., spontaneous microsaccades). While our data provides some  
480 evidence that an eye movement's visual consequences influences movement awareness  
481 (**Fig. 3c**), decoupling eye movements and their visual consequences in our paradigm revealed  
482 intention as another crucial factor for sensorimotor awareness of even the most minute of  
483 actions: We found low awareness of actions without intention (i.e., low sensitivity for  
484 spontaneous microsaccades from **Exp. 2**), and heightened awareness for actions congruent  
485 with an intention (i.e., increased sensitivity for intended microsaccades from **Exp. 1**) as well  
486 as intention-incongruent actions (i.e., increased sensitivity for unintended microsaccades from  
487 **Exp. 1**). Our data therefore support that fixating constitutes a process that is also intended and  
488 controlled much like the generation of a saccade.

489

## 490 **Conclusion**

491 For this study, we developed a novel paradigm that allowed us to dissociate the role of action  
492 intention and an action's sensory consequence for action awareness, two factors that previous  
493 research has typically confounded. Our results provide strong evidence that observers can, in  
494 principle, detect even the smallest possible eye movements. Action intention is the main driver  
495 of the perception of these tiny visual motor acts: Observers were significantly more sensitive  
496 to microsaccades when they intended to make or avoid them compared to when such  
497 microsaccades occurred spontaneously. Instantaneous sensory consequence did not lead to  
498 a similar increase in saccade sensitivity, demonstrating that sensorimotor contingencies did  
499 not enhance eye movement awareness. Taken together, our data support the conclusion that  
500 intention opens a gate to motor awareness even for unintended actions. Consequently, even  
501 microsaccades—the body's smallest actions—can be detected, whereas these movements  
502 typically escape awareness in the absence of a related intention.

503

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510

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618 **STAR Methods**

619

620 **RESOURCE AVAILABILITY**

621 **Lead contact**

622 Information and requests regarding resources for this study should be directed to and will be  
623 fulfilled by the lead contact, Jan-Nikolas Klanke [jan.klanke@hu-berlin.de]

624

625 **Materials availability**

626 There are no restrictions for the distribution of materials.

627

628 **Data and code availability**

629 • The preregistration, data, and all original code for **Experiment 1** has been deposited  
630 at the Open Science Framework and will be made publicly available as of the date of  
631 publication. [LINK WILL FOLLOW HERE].

632 • The preregistration, data, and all original code for **Experiment 2** has been deposited  
633 at the Open Science Framework and will be made publicly available as of the date of  
634 publication. [LINK WILL FOLLOW HERE].

635

636 **EXPERIMENTAL MODEL AND SUBJECT DETAILS**

637

638 In **Experiment 1**, a total of 10 participants were recruited by means of the “Psychologischer  
639 Experimental-Server Adlershof” (PESA) of the Humboldt-Universität zu Berlin. Participants  
640 (6 female, 1 diverse) had a mean age of 24.2 years old ( $SD = 4.6$ ,  $min = 18$ ,  $max = 31$ ), and  
641 all 10 were right-handed and 8 were right-eye dominant. All 10 participants had normal or  
642 corrected-to-normal vision. Participants were paid upon completion of the last session. The  
643 compensation was based on an hourly rate of €10/hour. Alternatively, psychology students  
644 could choose to obtain participation credit (1 credit per 15 minutes of participation) required for  
645 the successful completion of their bachelors’ program.

646 In **Experiment 2**, we recruited a total of 10 participants. Because we wanted a direct  
647 comparison between experiments, we tried to recruit the same participants for both  
648 experiments but were only able to successfully re-recruit 3 participants. The additional  
649 participants were recruited by means of the “Psychologischer Experimental-Server Adlershof”  
650 (PESA) of the Humboldt-Universität zu Berlin. Participants (7 female, 0 diverse) had a mean  
651 age of 26.5 years old ( $SD = 6.2$ ,  $min = 20$ ,  $max = 34$ ). All participants were right-handed, right-  
652 eye dominant, and had normal or corrected-to-normal vision. Participants were paid upon  
653 completion of each experiment: Compensation was based on an hourly rate of €8/hour and a  
654 bonus payment of €4 for the completion of the final session. Psychology students could again  
655 alternatively choose to gain participation credit (1 credit per 15 minutes of participation)  
656 required for the successful completion of their bachelors’ program.

657 **Experiment 1** and **2** were approved by the ethics committee (Ethikkommission) of the  
658 Institut für Psychologie at the Humboldt-Universität zu Berlin and conducted in agreement with  
659 the Declaration of Helsinki (‘World Medical Association Declaration of Helsinki’, 2013) and the  
660 General Data Protection Regulation (GDPR) of the EU. All participants provided informed  
661 consent in writing before the start of the first session.

662 For **Experiment 1** and **2**, we pre-registered three exclusion criteria that ensured that  
663 participants would not participate if they showed the inability to execute stable fixation and  
664 correct eye movements:

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- The inability to complete at least 4 blocks during the first experimental session due to fixation failures led to immediate exclusion from the experiment.
  - If we could not detect more than 3.5 (**Exp. 1**) or 2.5 microsaccades (**Exp. 2**) in the crucial time window (200-800 ms re stimulus onset) of trials with generated eye movements across each block of the first session, we likewise excluded the participant from further testing.
  - During data analysis, we double-checked the eye movement data offline. We excluded all participants that generated less than 150 microsaccades in the crucial time window (200-800 ms re stimulus onset) of generated microsaccade condition trials. Especially the second and third criteria were set to ensure that we would obtain enough data from each participant for the planned analyses.

677 In **Experiment 1**, no participant was excluded from data collection, but two participants  
678 decided against further participation after partially completing the first session and having  
679 trouble with the task and/or eye tracker. We could have excluded one participant for their  
680 overall low number of microsaccades after the completion of all trials (we were only able to  
681 detect 105 microsaccades in their data) but decided against it for economic reasons.

682 In **Experiment 2**, a total of six participants were excluded: four participants were  
683 excluded because they generated less than the required amount of microsaccades in the first  
684 session of the experiment, two participants because their overall number of microsaccades  
685 was vastly lower than 150. We could have excluded two more participants based on the third  
686 exclusion criterion (they generated slightly less than the required 150 microsaccades in total:  
687 134 and 139 respectively) but decided against it for economic reasons as well. Data collection  
688 for both experiments was heavily affected by COVID-19.

## 689 **METHOD DETAILS**

### 690 **Apparatus**

691 Participants were seated in a dark room in front of a screen at a distance of 340 cm and their  
692 head stabilized using a chin rest. We projected visual stimuli on a 141.0 x 250.2 cm video-  
693 projection screen (Stewart Silver 5D Deluxe; Stewart Filmscreen, Torrance, CA, USA) using a  
694 PROPixx DLP (960 x 540 pixels; VPixx Technologies Inc., Saint Bruno, QC, Canada) with a  
695 refresh rate of 1440 Hz. We recorded participants' eye positions of both eyes with a head-  
696 mounted eye tracker at a sampling rate of 500 Hz (EyeLink 2 Head Mount; SR Research,  
697 Ottawa, ON, Canada). The experiments were controlled on a workstation running the Debian 8  
698 operating system, using Matlab (Mathworks, Natick, MA), the Psychophysics Toolbox 3  
699 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) and the EyeLink Toolbox (Cornelissen et al.,  
700 2002).

701

### 702 **General Methods**

703 In **Experiment 1**, we wanted to compare intended microsaccades (i.e., eye movements  
704 generated under explicit movement instructions) and unintended (i.e., eye movements  
705 generated under explicit fixation instructions). We deployed an adapted version of a memory-  
706 guided microsaccade paradigm (Willeke et al., 2019), which presented the instructions for each  
707 trial during an initial fixation interval. During this interval, participants were either instructed to  
708 retrain their gaze position at the onscreen location indicated by the prolonged presentation of  
709 (only) the fixation point (50% of all trials), or to make an eye movement to another location  
710 specified by an eye movement target, presented in addition to the fixation point (50% of trials).  
711

712 The target was a white circle with the same diameter as the dot at the center of the fixation  
713 point (0.2 dva) and presented at a radial distance of either 0.2 dva, 0.4 dva, 0.6 dva, 0.8 dva,  
714 or 1 dva relative to the fixation dot. To introduce some variation to the microsaccade target  
715 location, we allowed for the microsaccade target to be displaced along the circumference of  
716 its radial distance to the fixation dot. This displacement was sampled from a normal distribution  
717 centered on 0 deg and with a standard deviation of 25 deg, resulting in onscreen locations of  
718 the microsaccade target that vary with smaller vertical than horizontal displacements.

719

#### 720 *Fixation-check interval*

721 Before the start of each trial, a target-shaped central fixation point appeared before an  
722 otherwise grey background. The fixation dot (inner part) had a diameter of 0.2 dva while the  
723 outer ring had a diameter of 0.6 dva. Before the onset of each trial, a fixation control routine  
724 was run that required the gaze position of the observer to be inside a circular region (3 dva in  
725 diameter) around the fixation point. The trial began when the fixation control was successful  
726 for at least 200 ms. The fixation point appeared at the onscreen location on which the stimulus  
727 presentation was centered in the following.

728

#### 729 *Fixation interval*

730 The fixation interval (present only in **Experiment 1**) started as soon as the outer ring of the  
731 fixation point disappeared. The interval duration varied randomly between 400 ms and 500 ms  
732 to avoid routine anticipatory eye movements. Fixation dot and microsaccade target remained  
733 visible for the entire duration of the fixation interval. Participants were instructed to keep their  
734 gaze locked on the fixation dot without making any eye movements as long as the dot was  
735 visible (i.e., for the duration of the fixation interval) in instructed fixation as well as instructed  
736 eye movement condition trials. If a microsaccade target was displayed additionally, participants  
737 were to memorize the onscreen location of the target and generate an eye movement to this  
738 location as soon as the fixation dot and microsaccade target disappeared (i.e., in the beginning  
739 of the stimulus presentation interval). In trials without microsaccade target presentation,  
740 participants were instructed to keep their eye position centered on the location of the fixation  
741 dot even after it disappeared.

742

#### 743 *Stimulus presentation interval*

744 The disappearance of the fixation point (inner part and outer part) indicated the start of the  
745 stimulus presentation interval. Stimulus presentation lasted for 1000 ms independent of  
746 condition. The position of the stimulus was determined randomly in each trial, but its midpoint  
747 was always within  $\pm 4$  dva relative to the screen center (horizontally as well as vertically).  
748 Between the stimulus presentation and the response interval, there was a short delay of 50 ms  
749 during which nothing was presented on the gray screen.

750

#### 751 *Response interval*

752 In the response interval, participants had to answer two simple yes-no questions and,  
753 depending on their response to these, a confidence rating. At first, we displayed the question  
754 "Did you perceive a stimulus flash?" on the screen. Participants could respond with either 'Yes!'  
755 or "No!" (both response options were presented onscreen below the question as well). In a  
756 second step, participants had to indicate whether they believe to have generated an eye  
757 movement. To this end, we displayed the question "Do you think you generated an eye  
758 movement?" together with the two response options from before. In both cases, responses

759 were submitted by pressing either the left or the right arrow (i.e., the arrow key in the direction  
760 of the chosen response option).

761 Participants' responses to these first two questions determined the presentation of  
762 the final stage of the response phase: If participants reported that they perceived a stimulus  
763 flash and that they thought they generated an eye movement, they were asked: "How sure  
764 are you that the stimulus was caused by an eye movement?". If they report to have perceived  
765 the stimulus flash but that they did not generate an eye movement, the question instead was:  
766 "How sure are you that the stimulus flash was not caused by an eye movement. To respond  
767 to this final question, participants had to choose one of four options displayed on a continuous  
768 scale: "not sure", "rather not sure", "rather sure", and "very sure". Participants selected their  
769 response by adjusting the position of a response prompt via the left and right arrow keys. If the  
770 response prompt assumes the desired position, participants logged-in their answers by  
771 pressing the space key. The lateralization of the response options (i.e., which option is  
772 displayed on which side of the stimulus center) remained the same for all sessions of one  
773 participant but was counterbalanced between participants.

774

## 775 **Variations in Experiment 2**

776 In **Experiment 2**, the fixation check interval, stimulus presentation interval, and response  
777 intervals were the same as in **Experiment 1**. Because we wanted to compare intended and  
778 unintended microsaccades from **Experiment 1** to spontaneous microsaccades, we removed  
779 the fixation interval before the stimulus presentation. Participants were informed that some  
780 microsaccades occurred spontaneously before the start of the first session and were informed  
781 that trials would abort if their gaze position deviated too much from the location indicated during  
782 the fixation check interval but received no further instruction regarding their eye movement  
783 behavior.

784

## 785 **Online control of eye positions**

786 During **Experiments 1** and **2**, participants' eye positions were tracked. Eye and screen  
787 coordinates were aligned by conducting standard nine-point calibration and validation  
788 procedures before the first trial of each session and whenever necessary. Blinks and  
789 deviations in gaze position ( $>1.5$  dva from fixation) were likewise monitored in both  
790 experiments and led to an abortion of the trial. Aborted trials were repeated at the end of each  
791 block in randomized order.

792

## 793 **Pre-processing**

794 Binocular microsaccades were detected using an algorithm described by Engbert and  
795 Mergenthaler (2006) in **Experiment 1** and **2**. For the velocity threshold, we used a  $\lambda$  of 5 and  
796 minimum microsaccade duration of 6 ms (3 data samples). To exclude potential over- or  
797 undershoot corrections, two microsaccades were merged if the interval between them was  
798 shorter than 10 ms (5 data samples).

799 For the replay of the retinal consequence of a microsaccade, we used the gaze  
800 positions of the dominant eye of each observer recorded during binocularly detected  
801 microsaccades. To allow for a direct comparison between the visibility of the stimulus between  
802 conditions, we only replayed the retinal consequences of microsaccades that were recorded  
803 in the crucial time window (200-800 ms after stimulus onset) of trials in which a generated  
804 microsaccade could render the stimulus visible. Additionally, we did not use the raw  
805 microsaccade data for the stimulus but pre-processed the recorded gaze trajectories. In a first

806 step, we re-centered the recorded gaze positions of each microsaccade on the origin by  
807 subtracting the coordinates of the first data sample from all remaining samples. In a second  
808 step, we excluded all gaze positions sampled after the microsaccade reaches its maximum  
809 amplitude because microsaccades frequently follow a curved trajectory that would likely lead  
810 to blurry or obscure percepts when replayed. If a microsaccade was shorter than 6 ms (3 data  
811 samples) before its maximum amplitude was reached, it was excluded altogether. In a third  
812 step, we projected the recorded eye positions onto the saccade vector by recalculating the  
813 location of each gaze position during the saccade relative to its amplitude. In step number four,  
814 we fit a gamma function to the velocity profile of the saccade vector. Optimal fits were  
815 determined by means of a root mean square error (RMSE) procedure. We additionally ensured  
816 the quality of the fits by excluding microsaccades for which the root mean square error deviated  
817 more than two standard deviations from the mean of all RMSEs of the same session from one  
818 participant. In step number five, we redistributed the gaze positions along the saccade vector  
819 based on the fitted velocities. To compensate for the difference between the frequency of the  
820 eye tracker (500 Hz) and the refresh rate of the projector used for the display (1440 Hz), the  
821 recalculation of the gaze position along the saccade vector was combined with an upsampling  
822 mechanism that padded the number of data points along the saccade vector according to the  
823 fitted velocity profile. In a sixth step, we checked that the upsampling mechanism did not lead  
824 to velocity profiles that were biologically implausible. To this end, we excluded microsaccades  
825 for which the peak velocity of the upsampled saccade vector was three times higher (or more)  
826 than the peak velocity as predicted for microsaccades of maximum amplitude (i.e., 1 dva) by  
827 the main sequence (a known curvilinear relationship between saccade amplitude and peak  
828 velocity, see\_Zuber et al., 1965) of the individual participant. In a final step, we inverted the  
829 coordinates of the upsampled saccade vector: We wanted to replay the retinal consequences  
830 of the image during a microsaccade back to the observers, and the retinal image is always  
831 shifts in the opposite direction of the eye movement. The same data preprocessing was used  
832 in **Experiment 1** and **2**.

833

#### 834 *Exclusion of trials from analyses.*

835 Because the replay differed between the first and later sessions of each participant, data  
836 obtained in session one were not considered in the main analysis. Trials in which a replayed  
837 microsaccade could render the stimulus visible and in which the participant generated at least  
838 one (additional) microsaccade as well as trials in which the participant generated more than  
839 one microsaccade in the stimulus presentation interval were likewise excluded. Note that trials  
840 with accidental microsaccade generation in the fixation interval of **Experiment 1** were not  
841 excluded: Participants were instructed to try and make an accurate eye movement again at  
842 the beginning of the stimulus presentation interval (i.e., after the disappearance of fixation point  
843 and saccade target) and only report for those eye movements.

844 We also disregarded trials with generated microsaccades larger than 1 dva and when  
845 the microsaccade failed to occur in the crucial time window of the stimulus (200-800 ms re  
846 stimulus onset). Finally, due to an error in the code, **Experiment 2** included the replay of  
847 microsaccades detected only monocularly. To account for this mistake, we excluded trials in  
848 which erroneously detected microsaccades were replayed from all analysis. For an overview  
849 over the number of valid trials per experiment, eye movement and stimulus condition, see  
850 **Table 1**).

		Stimulus conditions						Total:	
		No-stimulus Condition:		Generated microsaccades:		Replayed microsaccade:			
Number of Microsaccades:		0	1	0	1	0	1	0	1
Exp. 1	Intended microsaccades:	1374	691	2843	1319	2877	0 (1242)	7094	2010 (3252)
	Unintended microsaccade:	2492	268	4915	540	5017	0 (444)	12424	808 (1252)
Exp. 2	Spontaneous microsaccades:	4102	694	8222	1556	7476	0 (1379)	19800	2250 (3629)
Total:		7968	1653	15980	3415	15370	0 (3065)	39318	5068 (8133)

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**Table 1:** Overview over the number of valid trials in each stimulus display and eye movement condition.

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## QUANTIFICATION AND STATISTICAL ANALYSIS

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### Motor control for microsaccades

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#### *Saccade rates*

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To investigate motor control for microsaccades, we calculated individual saccade rates separately for different eye movement types: intended and unintended microsaccades (**Exp. 1**), as well as spontaneous microsaccades (**Exp. 2**). Saccade rates were calculated individually as the number of trials with a saccade divided by the number of all trials per participant (irrespective of stimulus condition). To assess how well participants could adept their instructed eye movements to the different target distances (ranging from 0.2 to 1 dva), we further categorized trials with intended microsaccades according to those distances. We predicted higher rates when participants were instructed to move their eyes (i.e., for intended microsaccades, **Exp. 1**), compared to when they were instructed to fixate (i.e., unintended microsaccades, **Exp. 1**), or when they received no instruction (spontaneous microsaccades, **Exp. 2**;  $rate_{spontaneous} \cong rate_{unintended} < rate_{intended}$ ).

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To determine if observers generated more saccades when instructed to do so in **Experiment 1**, we calculated a paired two-sided t-test for the within-subject comparison of intended and all unintended microsaccades. To assess the effect of target distance, we calculated a one-way repeated-measures analysis of variance (rmANOVA) on saccade rates with intended microsaccades, categorized based on target distance. To compare saccade rates between experiments, we employed two two-sided independent samples t-tests, comparing average rates of spontaneous microsaccades (**Exp. 2**) and unintended microsaccades (**Exp. 1**), as well as spontaneous (**Exp. 2**) and intended eye movements (**Exp. 1**).

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#### *Saccade amplitudes*

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Because we were interested in motor control for intended microsaccades, we calculated average amplitudes per participant and the five different target distances (0.2–1 dva). We did not pre-register specific hypotheses but would predict larger saccade amplitudes in trials with greater target distance.

884 To determine if greater target distances indeed led to saccades with larger  
885 amplitudes, we fit a linear mixed effects model to the unaggregated intended microsaccades  
886 from **Experiment 1**. The model predicted saccade amplitude with target distance by using a  
887 restricted maximum likelihood (REML) method. Participants were included in the model as  
888 random effects.

889

## 890 **Visual sensitivity to intra-saccadic stimulation**

### 891 *Eye movement generation*

892 We examined observer's visual stimulus sensitivity based on their responses to the first  
893 question "Did you perceive a stimulus flash?". We calculated individual hit rates based on the  
894 number of positive "Yes!"-responses in trials with stimulus. Similarly, individual false alarm  
895 rates were calculated based on "Yes!"-responses in trials without stimulus (no-stimulus  
896 condition trials). Because false alarm reports were very rare (40% of our participants did not  
897 report a single false alarm, and those who did only reported 1.57 false alarms on average), we  
898 decided not to calculate separate rates depending on saccade generation (as pre-registered),  
899 but combined rates for trials with and without eye movements. To determine if stimulus visibility  
900 depended on the type of eye movement generated, we determined different rates for trials with  
901 small intended and unintended saccades (**Exp. 1**), as well as spontaneous microsaccades  
902 (**Exp. 2**). To determine visual sensitivity per participant and condition, individual hit and false  
903 alarm rates were z-transformed and subtracted (i.e.,  $d' = z(\text{Hits}) - z(\text{FAs})$ ). We predicted that,  
904 while visual sensitivity should depend on eye movement generation (i.e.,  $d'_{0MS} < d'_{1MS}$ ), it  
905 should not differ between generated and replayed microsaccades (i.e.,  $d'_{\text{generated}} \cong d'_{\text{replayed}}$ ).  
906 Similarly, we did not expect visual sensitivity to differ based on eye movement type (i.e.,  
907  $d'_{\text{intended}} \cong d'_{\text{unintended}} \cong d'_{\text{spontaneous}}$ ).

908 To determine if the stimulus was invisible during stable fixation, we calculated  
909 averaged sensitivity indices per eye movement type and compared their corresponding 95%  
910 confidence intervals ( $CI_{95\%}$ ) against 0. Significant differences between eye movement types  
911 were determined by calculating a paired two-sided t-test for the within-subject comparison of  
912 intended and unintended eye movements (**Exp. 1**), and two-sided independent samples t-test  
913 for the comparison between combined intended and unintended microsaccades (**Exp. 1**) and  
914 spontaneous microsaccades (**Exp. 2**). The effect of eye movement generation in  
915 **Experiment 1** was determined by a two-way rmANOVA with visual sensitivity indices as the  
916 depended variable, and the stimulus condition (generated vs. replayed) and eye movement  
917 type (intended vs. unintended) as within-subject factors. To compare eye movements from  
918 different experiments, we calculated a mixed-measures ANOVA with stimulus condition  
919 (generated vs. replayed) as a within-subject factor and experiment (**Exp. 1** vs **Exp. 2**) as  
920 between-subject factor.

921

### 922 *Eye movement kinematics*

923 Because visual sensitivity should depend on the degree of retinal stabilization, we additionally  
924 calculated retinal velocity of the stimulus. To obtain retinal velocities, we subtracted the  
925 constant speed of the phase shift from the peak velocity of each microsaccade. We used  
926 directed speeds, i.e., positive values for rightward and negative values for leftward oriented  
927 phase shifts or saccade directions. Retinal velocity of 30 dva/s or less were labelled 'low',  
928 velocities surpassing 30 dva/s were labelled 'high'. We calculated hit and false alarm rates as  
929 well as visual sensitivity separately for generated and replayed eye movements of all three  
930 types (**Exp. 1**: intended and unintended microsaccades; **Exp. 2**: spontaneous microsaccades)

931 and according to the resulting retinal velocity of the stimulus (for more details see previous  
932 paragraph). We predicted that a higher retinal stability of the stimulus would lead to increased  
933 visual sensitivity. Consequently, microsaccades (irrespective of type) that lead to lower retinal  
934 velocities of the stimulus should yield higher sensitivity compared to trials with higher retinal  
935 velocity (i.e.,  $d'_{\text{high vel.}} < d'_{\text{low vel.}}$ ).

936 To determine if lower retinal stimulus velocities indeed led to higher visual sensitivity  
937 for eye movements from **Experiment 1**, we calculated a three-way rmANOVA with the within-  
938 subject factors retinal velocity (low vs. high velocity), stimulus condition (generated vs.  
939 replayed), and eye-movement type (intended vs. unintended). To compare these results to eye  
940 movements in **Experiment 2**, we calculated a three-way two-way mixed-measures ANOVA  
941 with the within-subject factors retinal velocity (low vs. high velocity) and stimulus condition  
942 (generated vs. replayed), and the factor experiment (**Exp. 1** vs. **Exp. 2**) as a between-subject  
943 factor. Significant differences between factors were determined by calculating paired two-sided  
944 t-test for within-subject comparisons or two-sided independent samples t-test to compare  
945 between experiments whenever necessary.

946 One participant was excluded from this analysis, because a hit rate in a particular  
947 condition could not be computed (i.e., unintended microsaccades that led to a high retinal  
948 velocity of the stimulus).

949

## 950 **Eye movement sensitivity**

### 951 *Stimulus presentation*

952 To determine how sensitive participants were towards their own eye movements, we analyzed  
953 participants responses to the second question of the response phase: “Do you think you  
954 generated an eye movement?”. To gain a better understanding of how eye movement  
955 awareness was affected by stimulus presentation, we calculated sensitivity separately for  
956 stimulus present and absent trials. Hit rates in stimulus present trials were calculated based  
957 trials with generated eye movement for which participants correctly reported believing to have  
958 generated a microsaccade. False alarm rates were, conversely, calculated based on trials with  
959 replayed microsaccades (i.e., in the absence of a generated saccade) for which participants  
960 incorrectly reported the same belief. In stimulus absent trials, hits and false alarm rates were  
961 calculated identically with the only difference that trials were taken solely from the no-stimulus  
962 condition. To assess if awareness differed between different types of eye movements, we  
963 additionally categorized trials by eye movement type; intended (**Exp. 1**), unintended (**Exp. 1**),  
964 and spontaneous microsaccades (**Exp. 2**). We expected low sensitivity towards spontaneous  
965 and unintended microsaccades, but increased sensitivity towards intended eye movements  
966 (i.e.,  $d'_{\text{spontaneous}} \cong d'_{\text{unintended}} < d'_{\text{intended}}$ ). No predictions about stimulus presentation were  
967 preregistered, however, we expected that—because the stimulus was presented saccade-  
968 contingently—stimulus presentation would facilitate detection for all types of microsaccades  
969 (i.e.,  $d'_{\text{absent}} < d'_{\text{present}}$ ).

970 To determine eye movement sensitivity in **Experiment 1**, we calculated a two-way  
971 rmANOVA with the within-subject factors eye movement type (intended vs. unintended) and  
972 stimulus presence (present vs. absent). Spontaneous microsaccades from **Experiment 2**  
973 were compared to results from the first experiment by calculating a two-way mixed-measures  
974 ANOVA with the within-subject factor stimulus presentation (absent vs. present) and the  
975 between subject factor experiment (Exp. 1 vs. Exp. 2). Paired two-sided t-test for within-subject



976 comparisons or two-sided independent samples t-test to compare between experiments were  
977 calculated to determine significance whenever necessary.

978

### 979 **Causal assignment**

980 To investigate if observers were able to detect whether their eye movements caused the high-  
981 temporal frequency stimulus to become visible, we analyzed their responses in the final part  
982 of the response phase. In this phase, we displayed one of two questions, depending on their  
983 previous responses: “Do you think your eye movements caused the stimulus flash?” if a  
984 participant had reported the presence of an eye movement, and “Do you think your eye  
985 movements did not cause the stimulus flash?” when they reported no eye movement. Unlike  
986 before, participants could respond on a 4-point scale, spanning from “very sure” to “very  
987 unsure”. While, according to our pre-registration, we planned to use this response schema to  
988 calculate meta- $d'$ , we ultimately decided that our data could be better understood by a simpler  
989 analysis: We assigned each response option a fixed score between -1.5 and 1.5 depending  
990 on the level of certainty (i.e., 1.5 for “very sure”, 0.5 for “rather sure”, -0.5 for “rather unsure”,  
991 and -1.5 for “very unsure”), before calculating average scores per stimulus condition and  
992 participants. Because we expected that participants ability to correctly assign causality to  
993 depend on eye movement awareness and because participants were similarly sensitivity  
994 towards their intended and unintended microsaccades in **Experiment 1**, we decided to neglect  
995 differences between these two types of saccades and categorized eye movements only by  
996 experiment for this analysis to increase its power.

997 We predicted that the ability to assign causality correctly directly depended on  
998 participants' eye movement awareness. Because eye movement sensitivity was higher in the  
999 first compared to the second experiment, we expected higher scores for **Experiment 1**  
1000 compared to **Experiment 2** (i.e.,  $\text{scores}_{\text{exp. 2}} < \text{scores}_{\text{exp. 1}}$ ).

1001 To analyze if observers assigned causality correctly in **Experiment 1**, we calculated  
1002 a two-way rmANOVA using certainty scores as the dependent variable and stimulus condition  
1003 (generated vs. replayed) and correctness of the assignment (correct vs. incorrect) as within-  
1004 subject factors. For **Experiment 2**, we replicated the analysis with an identical two-way  
1005 rmANOVA deploying the within-subject factors stimulus condition (generated vs. replayed) and  
1006 correctness of the assignment (correct vs. incorrect) again. Paired two-sided t-test for within-  
1007 subject comparisons or two-sided independent samples t-test to compare between  
1008 experiments were calculated to determine significance whenever necessary. One participant  
1009 was excluded in **Experiment 1**, another participant was excluded from **Experiment 2**—both  
1010 were excluded because we could not calculate certainty for trials with a microsaccade was  
1011 generated but none reported.

1012

### 1013 **Supplements**

1014

#### 1015 *Microsaccade rates*

1016 To better understand generation of intended microsaccade over small target distances  
1017 (**Exp. 1**), we compared rates for successive distances via paired t-test (all  $p$ -values reported  
1018 here are Bonferroni-corrected to adjust for multiple comparisons).

1019 While we found significant differences in rates for smaller target distances (0.2 dva  
1020 vs. 0.4 dva:  $t(9) = -3.27$ ,  $p = 0.039$ ; 0.4 dva vs. 0.6 dva:  $t(9) = -3.15$ ,  $p = 0.039$ ). We did not  
1021 observe significant differences for comparisons over larger distances (0.6 dva vs. 0.8 dva:  $t(9)$

1022 =  $-0.17$ ,  $p > 0.250$ ; 0.8 dva vs. 1.0 dva:  $t(9) = 0.57$ ,  $p > 0.250$ ). This supports the earlier  
1023 conclusion that saccade rates increase with increasing target distances.

1024 In a second step, we compared saccade rates of intended microsaccades for each  
1025 target distance to unintended microsaccades by again conducting two-sided paired t-tests for  
1026 each comparison (with Bonferroni-correction for multiple comparisons). Our testes revealed  
1027 insignificant differences between the rates of unintended and intended microsaccades when  
1028 the target distances were smaller or equal to 0.4 dva (unintended vs. 0.2 dva:  $t(9) = 1.64$ ,  $p >$   
1029  $0.250$ ; unintended vs. 0.4 dva:  $t(9) = 2.91$ ,  $p = 0.086$ ). When target distances exceeded  
1030 0.4 dva, however, the intended and unintended microsaccade rates differed increasingly  
1031 significantly (unintended vs. 0.6 dva:  $t(9) = 3.30$ ,  $p = 0.046$ ; unintended vs. 0.8 dva:  $t(9) = 3.78$ ,  
1032  $p = 0.022$ ; unintended vs. 0.8 dva:  $t(9) = 4.17$ ,  $p = 0.012$ ).

1033 Lastly, comparing between spontaneous (**Exp. 2**) and intended microsaccades  
1034 generated over the different target distances reveals no significant difference—irrespective of  
1035 target distance (all Bonferroni-correct  $ps > 0.250$ ).

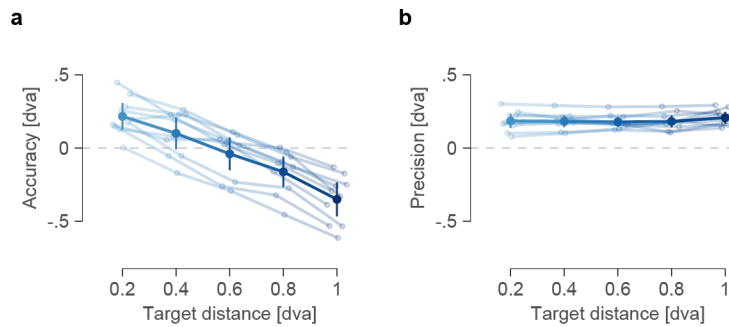
1036 Taken together, our finding suggests that task difficulty to reliably generate intentional  
1037 microsaccades increases when target distances get smaller—particularly when eye  
1038 movements must be generated without foveal anchor. Interestingly, insignificant differences  
1039 between microsaccade rates over small target distances and unintentional microsaccades  
1040 suggest that participants perform at a level compared to intended fixation when trying to make  
1041 eye movements smaller than 0.4 dva by memory. Of course, this result has to be interpreted  
1042 with caution, as the smallest saccades are also the hardest to detect with video-based eye  
1043 tracking equipment.

1044  
1045 *Accuracy and precision of intended microsaccades*

1046 To investigate motor control for intended microsaccades from **Experiment 1**, we calculated  
1047 averaged accuracy and precision of eye movements over the five target distances (ranging  
1048 from 0.2 to 1 dva) for each participant. We determined significance by calculating one-way  
1049 rmANOVAs with precision or accuracy as the depended variable and target distances (ranging  
1050 from 0.2 to 1 dva) as within-subject factor.

1051 We found that while our participants tended to overshoot when target distances were  
1052 small (0.2 dva:  $0.22 \pm 0.09$ , 0.4 dva:  $0.10 \pm 0.11$ ), accuracy was high for the medium distance  
1053 (0.6 dva:  $-0.04 \pm 0.11$ ). Conversely, for longer target distances, participants tended to  
1054 undershoot the target (0.8 dva:  $-0.16 \pm 0.10$ ; 1.0 dva:  $-0.35 \pm 0.12$ ; **Fig. S1a**). Unsurprisingly, a  
1055 one-way rmANOVA revealed a significant effect of target distance on saccade accuracy  
1056 ( $F(4,36) = 106.22$ ,  $p < 0.001$ ). While observers did adapt saccade amplitudes to the target  
1057 amplitudes (see section *Motor control for microsaccades* in results), the pattern of  
1058 overshooting eye movements over smaller target distances and undershooting eye  
1059 movements over larger target distances reveals a preference to generate microsaccades of  
1060 medium size.

1061 Precision on the other hand, is near identical over all target distances (0.2 dva:  
1062  $0.18 \pm 0.05$ ; 0.4 dva:  $0.18 \pm 0.04$ ; 0.6 dva:  $0.18 \pm 0.03$ ; 0.8 dva:  $0.18 \pm 0.04$ ; 1.0 dva:  $0.21 \pm 0.04$ ;  
1063 **Fig. S1b**), indicating that saccades were executed with equal precision irrespective of target  
1064 distance. We conducted a one-way rmANOVA precision as depended variable and target  
1065 distance as within-subject factor to corroborate this finding ( $F(4,36) = 1.23$ ,  $p > 0.250$ ).



1066  
1067 **Figure S1. Intended microsaccades overshoot small distances, undershoot long distances, but are executed with**  
1068 **precision regardless.** **a** Accuracy and **b** precision of intended microsaccades from Experiment 1. In all panels, small circles  
1069 indicate individual observers' means, filled dots represent sample means. Lines connect dots of individual participants. Error bars  
1070 indicate 95% confidence intervals.

1071  
1072 *Parameters of different eye movement types*

1073 To determine similarities and differences between the different types of eye movements, we  
1074 compared four different sets of parameters for intended, unintended (**Exp. 1**), and  
1075 spontaneous microsaccades (**Exp. 2**): amplitude, peak velocity, duration, and latency.

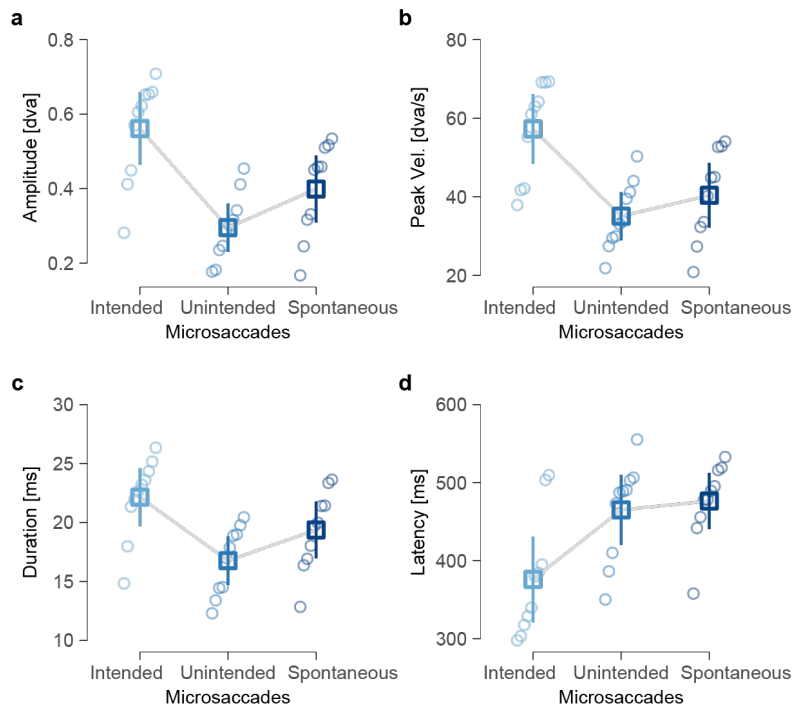
1076 In this analysis, we computed the means of individual eye movement parameters for  
1077 each participant before conducting comparisons between the different eye movement types.  
1078 We utilized two-alternative, paired t-tests when comparing eye movement from **Experiment 1**,  
1079 while for the comparison between **Experiment 1** and **2**, we employed two-alternative,  
1080 between-subject t-tests.

1081 Starting with the parameter amplitude, we found the largest amplitudes for intended  
1082 microsaccades ( $0.56 \pm 0.10$ ), while unintended microsaccades were markedly smaller  
1083 ( $0.30 \pm 0.06$ ). The difference between the two eye movement types was highly significant ( $t(9)$   
1084  $= 7.40$ ,  $p < 0.001$ ). Spontaneous microsaccades had an intermediary size ( $0.40 \pm 0.09$ ;  
1085 **Fig. S2a**). Comparing between experiments, we found spontaneous and unintended  
1086 microsaccades to be more similar in size ( $t(16.4) = -2.11$ ,  $p = 0.051$ ) compared to intended  
1087 microsaccades ( $t(17.9) = 2.77$ ,  $p = 0.01$ ).

1088 Turning to peak velocity next, we observed that intended microsaccades yielded the  
1089 highest peak velocities ( $57.27 \pm 8.83$ ). Unintended microsaccades, on the other hand, were  
1090 characterized by significantly lower peak velocities ( $35.07 \pm 6.15$ ;  $t(9) = 7.22$ ,  $p < 0.001$ ). Peak  
1091 velocities of spontaneous microsaccades were, again, on an intermediate level ( $40.38 \pm 8.26$ ;  
1092 **Fig. S2b**)—matching the peak velocity of unintended microsaccades more closely ( $t(16.6) =$   
1093  $-1.17$ ,  $p > 0.250$ ) than that of intended ones ( $t(17.9) = 3.16$ ,  $p = 0.005$ ).

1094 Next, we investigated how the durations of eye movements differed between intended  
1095 unintended, and spontaneous microsaccades. As before, our data revealed intended eye  
1096 movements to have the longest durations ( $22.15 \pm 2.46$ )—particularly compared to unintended  
1097 ( $16.76 \pm 2.07$ ) but also spontaneous microsaccades ( $19.37 \pm 2.41$ ; **Fig. S2c**). Here, only the  
1098 differences between intended and unintended microsaccades turned out to be significant ( $t(9)$   
1099  $= 8.49$ ,  $p < 0.001$ ), while both comparisons between experiments remained insignificant  
1100 (unintended vs spontaneous:  $t(17.6) = -1.86$ ,  $p = 0.080$ ; intended vs. spontaneous:  $t(18.0) =$   
1101  $1.82$ ,  $p = 0.084$ ), indicating that the duration of unintended microsaccades was even shorter  
1102 than that of spontaneous ones.

1103 Lastly, we looked at saccade latencies: We found the shortest latencies for intended  
1104 microsaccades ( $375.99 \pm 54.84$ ), with slightly longer latencies for unintended ( $465.12 \pm 44.92$ )  
1105 and spontaneous microsaccades ( $476.51 \pm 36.03$ ; **Fig. S2d**). Significant differences emerged  
1106 when comparing intended and unintended microsaccades ( $t(9) = -3.18, p = 0.011$ ) as well as  
1107 intended and spontaneous microsaccades ( $t(15.6) = -3.47, p = 0.003$ )—while the comparison  
1108 of unintended and spontaneous microsaccades remained insignificant ( $t(17.2) = -0.45, p >$   
1109  $0.250$ ).



1110

1111 **Figure S2. Unintended microsaccades are more similar to spontaneous than intended ones.** **a** Comparison of amplitudes  
1112 between intended, unintended (experiment 1), and spontaneous microsaccades (experiment 2). **b** Comparison of peak velocities  
1113 between eye movement types (same as in a). **c** Comparison of duration between eye movement types (same as in a).  
1114 **d** Comparison of latencies between eye movement types (same as in a). In all plots; small circle indicate individual observers'  
1115 means, squares represent sample means. Error bars indicate 95% confidence intervals.

1116

1117 *Microsaccade sensitivity as a function of stimulus perception (instead of presentation)*

1118 To corroborate the dependence of sensitivity on eye movement type and determine the  
1119 importance of the effect of stimulus presentation, we repeated our analysis of microsaccade  
1120 sensitivity with perceptual reports of the stimulus instead of stimulus presentation (i.e., stimulus  
1121 perceived vs. not perceived instead of stimulus present vs. absent).

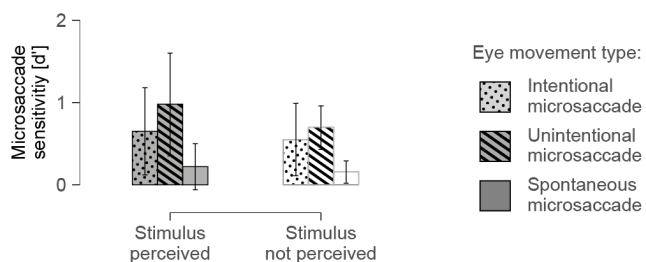
1122 To determine significance in **Experiment 1**, we calculated a two-way rmANOVA with  
1123 eye movements sensitivity as the dependent variable. Eye movement type (intended vs.  
1124 unintended) and perceptual reports (seen vs. not-seen) were included as within-subject  
1125 factors. Comparison between experiments were done with a two-way mixed-measures  
1126 ANOVA that, again, used eye movement sensitivity as the dependent variable and perceptual  
1127 report (seen vs. not-seen) as within-subject factor and experiment (**Exp. 1** vs. **Exp. 2**) as  
1128 between-subject factor. Paired two-sided t-test or two-sided independent samples t-test were  
1129 calculated to determine significance whenever necessary as before.

1130 For **Experiment 1**, we found that observers were sensitive towards intended ( $d' =$   
1131  $0.60 \pm 0.47$ ), and unintended microsaccades ( $d' = 0.84 \pm 0.40$ ; **Fig. S3a**) and a two-way  
1132 rmANOVA revealed no significant difference between the types of eye movements (intended

1133 vs. unintended;  $F(1,9) = 0.69, p > 0.250$ ). The perception of the stimulus had no significant  
1134 influence in this analysis (stimulus perceived vs. not perceived;  $F(1,9) = 2.31, p = 0.163$ ),  
1135 indicating that observers' microsaccade sensitivity remained unaffected irrespective of  
1136 whether they perceived the stimulus. The interaction of eye movement and stimulus percept  
1137 remained insignificant as well ( $F(1,9) = 0.45, p > 0.250$ ).

1138 Comparing these results to **Experiment 2**, we found that participants were less  
1139 sensitive to spontaneous microsaccades, irrespective of whether they reported to have seen  
1140 the stimulus ( $d' = 0.22 \pm 0.28$ ) or not ( $d' = 0.16 \pm 0.14$ ; **Fig. S3a**). Predictably, a two-way mixed-  
1141 measures ANOVA revealed that microsaccade sensitivity only differed significantly when  
1142 comparing eye movements from different experiments ( $F(1,18) = 11.61, p = 0.003$ ), while  
1143 stimulus perception failed to have a significant effect on sensitivity (stimulus perceived vs. not  
1144 perceived;  $F(1,18) = 2.39, p = 0.139$ ). The interaction of experiment and stimulus perception  
1145 remained insignificant as well ( $F(1,18) = 0.59, p > 0.250$ ).

1146 Taken together our results suggest that the parameters of unintended microsaccades  
1147 more closely resemble those of spontaneous microsaccades than intended eye movements.  
1148



1149  
1150 **Figure S3. Microsaccade sensitivity based on perceptual reports.**

1151  
1152 *Microsaccade (mis-) detection based on stimulus condition and perceptual report.*  
1153 Here we report the proportion of correctly detected eye movement (hits) as well as mis-  
1154 detected eye movements (false alarms) for intended, unintended (**Exp. 1**), and spontaneous  
1155 microsaccades (**Exp. 2**). Eye movement reports are further split according to the visual  
1156 stimulus condition (generated saccade, replayed saccade, and stimulus absent) and  
1157 perceptual report of the visual stimulus (stimulus perceived and stimulus not perceived). False  
1158 alarm rates could not be calculated for trials with generated microsaccades for which observers  
1159 reported having perceived the stimulus as reports of the stimulus as it was impossible to see  
1160 the stimulus in the absence of a microsaccade and false alarms of the stimulus were  
1161 exceedingly rare. We equally failed to calculate hit and false alarms in stimulus absent trials in  
1162 which a stimulus percept was reported for the same reason.

1163 We examined detection of intended and unintended microsaccades (**Exp. 1**) for  
1164 generated and replayed microsaccades in relation to their perceptual consequences first. To  
1165 this end, we calculated a three-way rmANOVA with hit rates as the depended variable and the  
1166 within-subject factors eye-movement type (intended vs. unintended), stimulus condition  
1167 (generated vs. replayed), and perceptual reports (perceived vs. not perceived) as the  
1168 independent variables. The rmANOVA revealed a significant main effect of eye movement  
1169 (intended vs. unintended:  $F(1,8) = 136.70, p < 0.001$ ) indicating that intended eye movements  
1170 (hits =  $0.86 \pm 0.06$ ) were detected significantly more often than unintended ones (hits =  
1171  $0.24 \pm 0.15$ ; **Fig. S4**). We additionally found a significant effect of perceptual report (stimulus

1172 perceived vs. not perceived:  $F(1,8) = 8.75, p = 0.018$ ), indicating that eye movements were  
1173 additionally detected more often in trials in which a stimulus was perceived (hit =  $0.79 \pm 0.07$ )  
1174 compared to when it was not (hits =  $0.72 \pm 0.08$ ; **Fig. S4**). The main effect of stimulus condition  
1175 was not significant (generated vs. replayed:  $F(1,8) = 0.56, p > 0.250$ ) and neither was any  
1176 interaction (all  $ps > 0.08$ ). One participant was excluded from this analysis because a lack of  
1177 trials with unintended generated eye movement for which no stimulus percept was reported.

1178 Comparing saccade detection rates between experiments, we calculated a three-way  
1179 rmANOVA with the within-subject factors stimulus conditions and perceptual report, as well as  
1180 the between-subject factor experiment (**Exp. 1** vs. **Exp. 2**) next. We found a significant main  
1181 effect of perceptual report (perceived vs. not perceived:  $F(1,18) = 11.34, p = 0.003$ ) and a  
1182 significant main effect of experiment (**Exp. 1** vs. **Exp. 2**:  $F(1,18) = 34.50, p < 0.001$ ), while the  
1183 main effect of stimulus presentation and all interactions remained insignificant (all  $ps > 0.059$ ).  
1184 Post-hoc comparisons revealed that—despite the low detection rates for unintended  
1185 microsaccades from our first experiment—combined detection rates were still significantly  
1186 higher in experiment one compared to the second experiment ( $t(12.7) = 5.90, p < 0.001$ ;  
1187 **Exp. 1**: hits =  $0.75 \pm 0.06$ ; **Exp. 2**: hit =  $0.36 \pm 0.13$ ; **Fig. S4**). Additional post-hoc comparisons  
1188 for the significant main effect perceptual report replicate the findings from our previous analysis  
1189 that trials in which a stimulus was perceived (hit =  $0.68 \pm 0.11$ ) led to significantly higher  
1190 detection rates (not perceived: hits =  $0.50 \pm 0.15$ ; **Fig. S4**), even when spontaneous  
1191 microsaccades were considered.

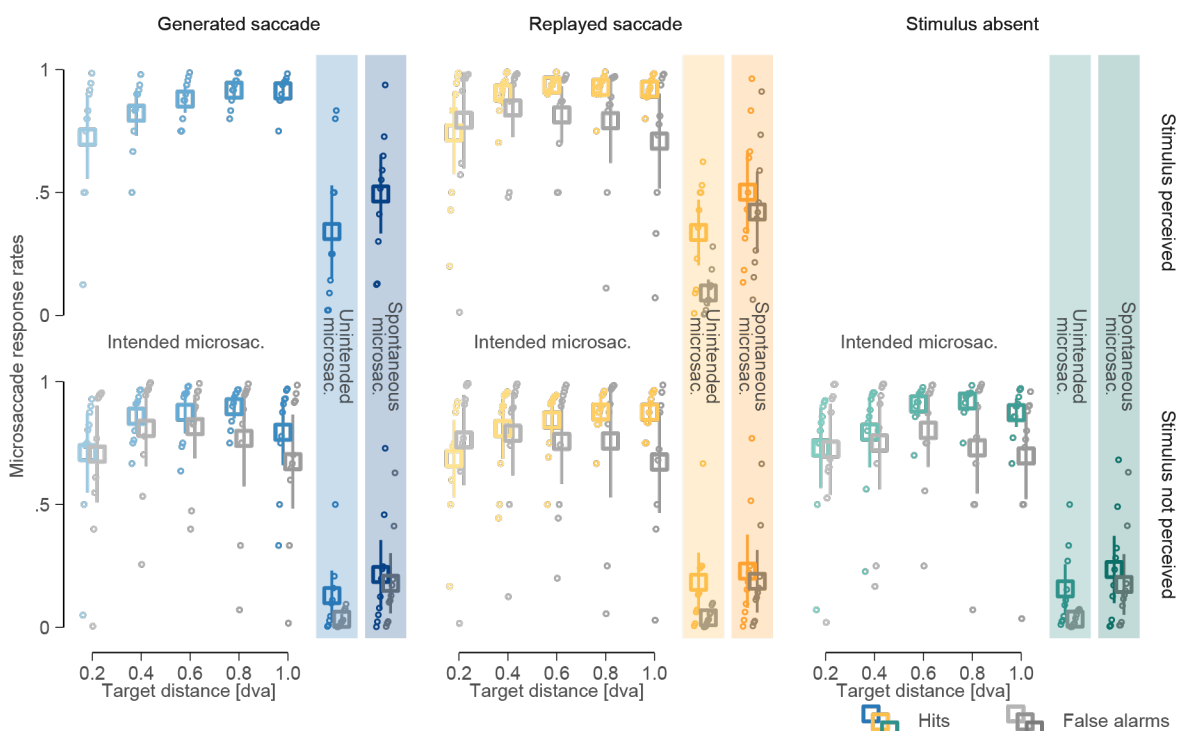
1192 We analyzed false alarms in a separate analysis. Starting with trials from  
1193 **Experiment 1** in which participants reported not having perceived a stimulus, we calculated a  
1194 two-way rmANOVA with false alarm rates as the dependent variable and the within-subject  
1195 factors stimulus condition (generated vs. replayed) and eye movement types (intended vs.  
1196 unintended) as the dependent variables. The test revealed a significant effect of eye movement  
1197 (intended vs unintended:  $F(1,9) = 86.10, p < 0.001$ ), while stimulus condition (generated vs  
1198 replayed:  $F(1,9) = 0.37, p > 0.250$ ) and their interaction ( $F(1,9) = 1.20, p > 0.250$ ) remained  
1199 insignificant. Post-hoc comparisons revealed that false alarms are reported significantly more  
1200 often for intended compared to unintended microsaccades ( $t(9) = 9.27, p < 0.001$ ; intended:  
1201 FAs =  $0.75 \pm 0.18$ ; unintended: FAs =  $0.04 \pm 0.02$ ; **Fig. S4**), indicating that intending to generate  
1202 an eye movement increases the likelihood of reporting successful eye movement generation  
1203 even in the absence of a microsaccade. Repeating this analysis for the comparison between  
1204 experiments reproduced the same results: A two-way mixed measures ANOVA indicated that  
1205 false alarm rates only differ when comparing eye movements between experiments (Exp. 1 vs  
1206 Exp. 2:  $F(1,18) = 22.61, p < 0.001$ ) not when comparing stimuli conditions with the  
1207 experiments (generated vs replayed:  $F(1,18) = 0.14, p > 0.250$ ; interaction:  $F(1,18) = 2.03, p$   
1208 =  $0.172$ ; **Fig. S4**): Observers were more likely to falsely report successful eye movement  
1209 generation when intending to make (or suppress) an eye movement (**Exp. 1**: FAs =  $0.63 \pm 0.15$ )  
1210 compared to when they did not (**Exp. 2**: FAs =  $0.18 \pm 0.14$ ), supporting our previous supposition  
1211 that false alarm rates were increased because of observers' intention to saccade—facilitated  
1212 only in **Experiment 1**.

1213 Lastly, to investigate how seeing the stimulus affected false alarms, we calculated a  
1214 two-way rmANOVA with the factors eye movement type (intended vs. unintended) and  
1215 stimulus report (perceived vs. not perceived) for replayed eye movements only (since false  
1216 alarms depending on stimulus perception are distributed equally only for replayed eye  
1217 movements). We again found a significant main effect of eye movement ( $F(1,9) = 97.90, p <$   
1218  $0.001$ ), indicating a much higher false alarm rate for intended (FAs =  $0.77 \pm 0.16$ ) than for

1219 unintended microsaccades (FAs =  $0.07 \pm 0.04$ ; **Fig. S4**). In addition, the factor perceptual report  
 1220 was significant as well ( $F(1,9) = 6.60$ ,  $p = 0.030$ ), with slightly higher false alarm rates for trials  
 1221 in which a stimulus was perceived (FAs =  $0.67 \pm 0.12$ ) than trials in which it remained  
 1222 imperceptible (FAs =  $0.62 \pm 0.16$ ). However, a two-alternative post-hoc t-test revealed this  
 1223 comparison to be marginal ( $t(9) = 2.21$ ,  $p = 0.054$ ; **Fig. S4**). The interaction between eye  
 1224 movement type and perceptual report remained insignificant ( $F(1,9) = 0.003$ ,  $p > 0.250$ ).

1225 We again found the same results when comparing between experiments: A two-way  
 1226 mixed-measures ANOVA revealed a significant effect of the between-subject factor experiment  
 1227 (**Exp. 1 vs Exp. 2**:  $F(1,18) = 15.91$ ,  $p = 0.001$ ; **Fig. S4**), indicating that observers misreported  
 1228 an eye movement more often in our first experiment (FAs =  $0.65 \pm 0.14$ ) compared to  
 1229 **Experiment 2** (FAs =  $0.30 \pm 0.14$ ). We also found a significant effect of perceptual report  
 1230 (perceived vs not perceived:  $F(1,18) = 9.53$ ,  $p = 0.006$ ; **Fig. S4**), with significantly higher false  
 1231 alarm rates in trials in which observers saw the stimulus ( $t(19) = 2.89$ ,  $p = 0.009$ ; perceived:  
 1232 FAs =  $0.55 \pm 0.12$ ; not perceived: FAs =  $0.40 \pm 0.14$ ). We found no interaction between  
 1233 experiment and stimulus perception ( $F(1,18) = 3.70$ ,  $p = 0.070$ ).

1234 Taken together, our analyses suggest that it is neither hits, nor false alarms alone that  
 1235 result in a similar sensitivity for intended and unintended microsaccades. Instead, it is their  
 1236 shared ratio of hits to false alarms that produces the effect reported in the results section.  
 1237



1238 **Figure S4. High rates for intended low rates for unintended and spontaneous microsaccades.** Comparison of hit and false  
 1239 alarm rates for intended (**Exp. 1**), unintended (**Exp. 1**), as well as spontaneous microsaccades (**Exp. 2**). The data is split into  
 1240 different panels according to stimulus presentation condition (generated microsaccades in blue, replayed saccades in yellow, and  
 1241 stimulus-absent condition trials in green hues) and according to perceptual reports (stimulus perceived in upper, stimulus not  
 1242 perceived in lower panels). Data for intended microsaccades is additionally presented over five different target distances (ranging  
 1243 from 0.2 to 1 dva).  
 1244

1245 Finally, we examined if target distance affected detection of generated and replayed intended  
 1246 microsaccades in different stimulus conditions and depending on perceptual reports. Our  
 1247 three-way rmANOVA revealed a significant main effect of target distance ( $F(1.6,12.6) = 0.39$ ,

1248  $p = 0.047$ ; test results are reported after Huynh-Feldt correction for violation of sphericity), and  
1249 insignificant main effects of stimulus condition ( $F(1,8) = 1.29, p > 0.250$ ) and perceptual report  
1250 ( $F(1,8) = 2.52, p = 0.151$ ). Interactions were all insignificant (all  $p$ s  $> 0.062$ ). Post-hoc t-tests  
1251 revealed significant differences between hit rates in trials with a target distance of 0.2 dva and  
1252 all four remaining target distances (all Bonferroni-corrected  $p \leq 0.011$ ). No other comparison  
1253 reached significance (all remaining Bonferroni-corrected  $p > 0.111$ ). A two-way rmANOVA for  
1254 false alarms in all stimulus conditions but only those trials for which participants reported no  
1255 stimulus revealed no significant effects (all  $p$ s  $> 0.250$ ). Together, these results indicate that,  
1256 while hit rates were positively affected by saccade amplitude—with hit rates being the lowest  
1257 when saccades are the smallest—false alarm rates stayed constant over the target distances.