

# Stimulus-driven visual attention in mice

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In primates, stimulus-driven changes in visual attention can facilitate or hinder perceptual performance, depending on the location and timing of the stimulus event. Mice have emerged as a powerful model for studying visual circuits and behavior; however, it is unclear whether mice show similar interactions between stimulus events and visual attention during perceptual decisions. To investigate this, we trained head-fixed mice to detect a near-threshold change in visual orientation and tested how performance was altered by task-irrelevant stimuli that occurred at different times and locations with respect to the orientation change. We found that task-irrelevant stimuli strongly affected mouse performance. Specifically, stimulus-driven attention in mice followed a similar time course as that in other species: The decreases in reaction times fully emerged between 250 and 400 ms after the stimulus event, and detection accuracy was not affected. However, the effects of stimulus-driven attention on behavior in mice were insensitive to stimulus-event location, an aspect different from what is known in primates. In contrast, reaction times in mice were reduced at longer delays after the task-irrelevant stimulus event regardless of its spatial congruence to the target. These results highlight the strengths and limitations of using mice as a model for studying higher-order visual functions.

## Introduction

Visual attention is a fundamental mechanism that enables the selective processing of behaviorally relevant information (Carrasco, 2011). Attention is usually directed voluntarily toward task-relevant events but may also be driven involuntarily by salient stimulus events. Both aspects of visual attention can occur covertly, without physically orienting toward the event (Posner & Cohen, 1984).

Stimulus-driven attention in primates has been studied by measuring how the ability to detect or discriminate a visual target is altered by a brief but salient event preceding the target. Performance depends on the timing and location of the event with respect to the target, providing a distinctive signature for stimulus-driven attention (Figure 1). The time course of stimulus-driven attention begins showing its effects a few milliseconds after the stimulus event but takes several hundred milliseconds to fully unfold; reaction times are reduced for stimulus events presented 100 ms before target appearance and continue to decrease for delays up to about half a second (Egeth & Yantis, 1997; Klein, 2000). The location of the stimulus event also matters. Performance is faster when the target is presented at the same location as the preceding stimulus event (i.e., congruent), but only for delays up to around 200 ms. At longer delays, the effect of location flips, and performance is then faster for targets presented at a different location than the stimulus event

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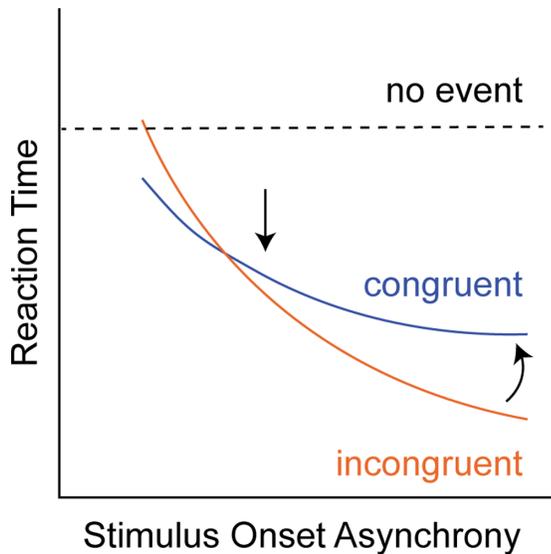


Figure 1. Illustration of stimulus-driven attention. Schematic data illustrating the main features of stimulus-driven attention in humans. Reaction times without a stimulus event are represented by the dashed horizontal line. Reaction times with stimulus events on the same side as a target (congruent, blue) and the opposite side as the target (incongruent, orange) are plotted for a range of delays between the stimulus event and target onset (stimulus-onset asynchrony [SOA]). At short SOAs, the subjects were faster to respond to congruent targets compared with incongruent targets. At longer SOAs, the subjects were faster to respond to incongruent targets compared with congruent targets; this phenomenon is known as inhibition of return.

(i.e., incongruent) (Posner & Cohen, 1984). This flip in the effect of location, referred to as “inhibition of return,” is believed to promote the sampling of new visual stimuli by suppressing the revisiting of salient but previously viewed, or previously attended, locations (Klein, 2000).

Some features of stimulus-driven attention are conserved across different species and others are not. The time course of stimulus-driven attention in non-human primates, owls, and archer fish resembles that in humans—fast acting but taking hundreds of milliseconds to unfold (Bowman, Brown, Kertzman, Schwarz, & Robinson, 1993; Gabay, Leibovich, Ben-Simon, Henik, & Segev, 2013; Lev-Ari, Zahar, Agarwal, & Gutfreund, 2020). However, there are individual differences in the timing and presence of facilitation and inhibition of return in owls and archer fish (Gabay et al., 2013; Lev-Ari et al., 2020). Additionally, pigeons do not show inhibition of return, although this may have to do with the specificities of the task (Gibson, Juricevic, Shettleworth, Pratt, & Klein, 2005).

Rodents, and especially mice, provide a potentially powerful animal model to study perceptual decision making (Carandini & Churchland, 2013). Much of what we know about attention in rodents is based on freely moving animals performing nose-poke tasks (Bushnell & Strupp, 2008; Robbins, 2002), demonstrating that rodents can use visual cues to decrease their reaction times (Bushnell, 1995; Weese, Phillips, & Brown, 1999; You & Mysore, 2020). There is also some evidence for stimulus-driven attention in rodents, with mixed results. Some studies have found that reaction times depend on both temporal and spatial properties of stimulus events and targets (Marote & Xavier, 2011), whereas others have been inconclusive (Wagner, Baker, & Rostron, 2014). Head-fixed approaches can be advantageous when studying visual perception, particularly when distinguishing between covert attention and overt orienting (Carandini & Churchland, 2013). Head-fixed mice can use spatial cues to covertly allocate visual attention, with effects on performance accuracy and reaction time similar to those found in primates (Krauzlis & Wang, 2018), but there has not yet been a study in head-fixed mice exploring the distinctive temporal and spatial properties of stimulus-driven attention.

Here, we studied stimulus-driven covert attention in mice. We trained head-fixed mice to report the detection of a near-threshold change in visual orientation by licking a central spout and tested how performance was altered by task-irrelevant stimuli flashed at different times and locations with respect to the task-relevant orientation change. We found that flashed stimuli produced systematic reductions in reaction times that followed the well-known time course of stimulus-driven attention, but there was no difference in the effect of spatially congruent versus incongruent events. We conclude that visual perceptual decisions in mice are strongly affected by a form of stimulus-driven attention but find no evidence for inhibition of return.

## Materials and methods

### Animals

Procedures were conducted on eight (four males, four females) wild-type C57BL/6J mice, (stock #000664; The Jackson Laboratory, Bar Harbor, ME). Mice were housed on a reverse 12-hour-light/12-hour-dark cycle, with the dark phase occurring from 8 a.m. to 8 p.m. Behavioral training and experiments were all performed in the dark portion of the cycle. Experimental and husbandry procedures were approved by the National Institutes of Health Institutional Animal Care and Use Committee and complied with Public Health Service

policy on the humane care and use of laboratory animals.

## Stereotaxic surgery

All mice had a head-holder surgically implanted at 6 to 8 weeks of age prior to the start of the experiments using procedures described previously (Krauzlis, Nichols, Rangarajan, McAlonan, Goldstein, Yochelson, & Wang, 2020). Briefly, animals were anesthetized with isoflurane (4% induction, 0.8%–1.5% maintenance) and given dexamethasone to reduce inflammation (1.6 mg/kg). An incision was made on the scalp along the midline, and the skull was exposed so that a custom-designed titanium head post could be secured to the skull with Metabond (Parkell, Edgewood, NY). The wound edge was then sealed using tissue adhesive (Vetbond; 3M, St. Paul, MN). After surgery, mice were subcutaneously given meloxicam (2 mg/kg) to minimize discomfort daily for up to 3 days.

## Food control

Mice were placed on a food-controlled schedule after they recovered from surgery and returned to >95% of their pre-surgery weight (~7–9 days). The health of all mice was monitored daily throughout the experiment, and food intake was regulated so that mouse weight was maintained at 85% or higher than that of ad lib food access. Mice had ad lib access to water and controlled access to dry food, which they were able to augment during experiments with nutritionally complete 8% soy-based infant formula (Similac; Abbott, Lake Forest, IL). Mice were introduced to handling and experimental procedures by receiving soy-based fluid from a sipper tube under manual control while the head was restrained. When the mice had become acclimated to the sipper tube, they received soy-based fluid automatically under computer control in the behavioral apparatus.

## Behavioral apparatus

The behavioral apparatus consisted of a custom-built booth that displayed visual stimuli on the left- and right-hand sides of the head-fixed mouse that was coupled to their locomotion using an apparatus described in detail elsewhere (Krauzlis et al., 2020). Two walls of the booth incorporated a pair of liquid-crystal displays (model VG2439; ViewSonic Corporation, Brea, CA) and positioned at a 45° angle from the midline of the animal so that the displays were centered on the right or left eye and subtended by ~90° horizontal and ~55° vertical of the visual hemifield. The viewing

distance from the mouse to the screen was ~27.5 cm. Sound-absorbent material lined the inside of the booth to reduce noise.

Experiments were computer controlled using a modified version of the Plexon–Datapixx–Psychtoolbox system (PLDAPS) (Eastman & Huk, 2012) that omitted the Plexon device, but included a Datapixx peripheral (Vpixx Technologies, Saint-Bruno, QC, Canada) and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) for MATLAB (MathWorks, Natick, MA) for generating visual stimuli, run on a Mac Pro (Apple Inc., Cupertino, CA). The Datapixx device allowed for autonomously timed control over analog and digital inputs and outputs synchronized to the visual display stimuli. A reward spout was located near the mouth of the mouse and lick contacts on the spout were detected by a piezo sensor (Mide Technology, Woburn, MA) and custom electronics. Rewards consisted of a small volume (~5–10  $\mu$ L) of 8% solution of Similac soy-based infant formula and was delivered via a peristaltic pump (Instech Laboratories, Plymouth Meeting, PA). An aversive stimulus, an airpuff, could be delivered through a second spout located slightly above the reward spout, which was controlled through solenoids (Parker-Hannifin, Mayfield Heights, OH).

## Visual detection tasks

The detection tasks used in this study were three variations of the attention task we used previously (Krauzlis & Wang, 2018). For each of the three experiments, animals were run in daily sessions that each produced 150 to 650 trials, and data were pooled across sessions. Experiments were organized in blocks of randomly shuffled trials, and each trial consisted of a sequence of epochs that the mouse passed through by walking or running on a wheel. Each epoch was defined by the particular stimuli presented on the visual displays, and the duration of each epoch was determined by either the timing of that epoch or the time that it took for the mouse to travel a randomized distance on the wheel. The key visual event in every task was the detection of a change in the orientation of a Gabor patch visual stimulus, which the mouse reported by contacting the lick spout. The three experiments were designed to test how the stimulus events before this orientation change affected detection performance.

### Experiment 1. Luminance-change event

This experiment contained equal numbers of trials with and without a task-irrelevant stimulus event, randomly interleaved, intended to probe stimulus-driven changes in attention. Trials without a task-irrelevant stimulus event followed a standard

sequence of three epochs. In the first epoch (“noise”), lasting for 0.6 to 1.2 s, the uniform gray of the intertrial interval was changed to pink visual noise with a root mean square contrast of 3.3%.

In the second epoch (“delay”), two vertically oriented Gabor patches were added to the pink noise, centered on the left or right visual display. The sinusoidal grating of the Gabor patch (87% Michelson contrast) had a spatial frequency of 0.1 cycles per degree and was modulated by a Gaussian envelope with a full width at half maximum of  $18^\circ$  ( $SD = 7.5^\circ$ ). The phase of the grating was incremented in proportion to the wheel rotation and updated on every monitor refresh so that the sinusoidal pattern displaced on the screen matched the distance that the mouse traveled on the wheel. The Gabor patch on the left drifted leftward, and the Gabor patch on the right drifted rightward, consistent with optic flow. The delay epoch was presented for 1.25 to 2.5 s.

In the third epoch (“change?”), the visual stimuli depended on whether the trial was a change or no-change condition; the two trial types were equally likely, randomly interleaved within a block, and matched for running distance (77–154 cm). On change trials, the Gabor patch on either the left- or right-hand side changed its orientation (left and right changes were equally likely and randomly interleaved within a block). Left Gabor changes rotated clockwise, and right Gabor changes rotated counterclockwise. On no-change trials, neither Gabor patch changed orientation, so that the epoch unfolded as a seamless extension of the previous delay epoch. The average luminance across the visual display in these three epochs was 4 to 8  $\text{cd}/\text{m}^2$ .

Trials with a task-irrelevant stimulus event included the same three epochs above plus two additional epochs: “stimulus event” and “offset delay.” The stimulus event epoch lasted 100 ms and immediately followed the initial delay epoch. For Experiment 1, this stimulus event consisted of a brightening of the Gabor patch, which increased the contrast from 87% to 99% and its overall luminance by 9.4  $\text{cd}/\text{m}^2$  and is therefore referred to as “flash.” The flash event occurred on half the trials and was equally likely to occur on either the left or right side; hence, the location of the flash was independent of the location of the possible change event.

The flash event was followed by an offset delay epoch that allowed us to match the timing of the change event across trial types; the time from the start of the delay epoch to the end of the offset delay epoch ranged from 1.25 to 2.5 s to match the time of the delay epoch in trials without a flash event. The offset delay epoch contained the same visual stimuli as the second epoch (delay) and lasted 50, 150, 300, 500, or 750 ms, depending on the delays between the flash event and target onset (stimulus-onset asynchrony [SOA]); each SOA was randomly interleaved and equally likely. Finally, the change epoch followed the offset delay

epoch, same as in trials without a flash event; in trials with a change, the orientation change was equally likely to occur on either the same side or the opposite side as the previous flash event.

In all trials, the task of the mouse was to lick the spout when he or she detected a change in the orientation of the Gabor patch. Mice had to lick within a 600-ms response window starting 200 ms after the orientation change to score a “hit” and receive a fluid reward. If the mouse failed to lick within this window after an orientation change, the trial was scored as a “miss” and no reward was given but no other penalty was applied. If the mouse licked early during the delay epoch, the trial was aborted and not counted. Premature licks were discouraged with timeouts and possible airpuff penalties (Krauzlis & Wang, 2018). In trials with a flash event, if the mouse licked after the stimulus but before the response window, the mouse was not punished and the trial progressed forward, following the rule that the stimulus event should be considered behaviorally irrelevant. On no-change trials, if the mouse’s first lick in the change epoch fell within the same response window, the trial was scored as a false alarm; if not, the trial was scored as a correct reject. To promote consistent performance, correct reject trials included a safety-net epoch where the Gabor underwent a suprathreshold  $30^\circ$  orientation change and mice could collect a reward by licking in a comparable response window (Krauzlis & Wang, 2018). Responses in the safety-net epoch were not used in the data analysis.

Experiment 1 was run in blocks of 80 trials. Each block was designed such that there was at least one of each trial type, considering each possible combination of orientation change (change or no-change), change side (left or right), stimulus event (flash or no-flash), flash congruency (congruent or incongruent), and SOA (150, 250, 400, 600, or 850 ms) was present. In other words, within each block, half of the trials (40) had an orientation change and the other half did not. In the half with an orientation change, 20 trials had the change occur on the left Gabor patch and in remaining trials on the right. There was an equal number of trials with and without flash events (10) in each of these 20 trials, five of which were congruent with the side of orientation change and five of which were incongruent. Each of the five congruent and incongruent trials had a different SOA, matching the five SOAs used in the task. The same was true on the other 40 trials without an orientation change, except that they were not divided into change on the left or right; for trials with a flash event, 10 had the flash event on the left and 10 on the right, with two trials for each different SOA used in the task. The order of the trials within a block was randomly interleaved. This block counterbalancing was done to minimize possible behavioral biases related to frequency matching.

### Experiment 2. Annulus event

This experiment was identical to Experiment 1 except that the flash was replaced by an annulus that was added to the pink noise and Gabor patch and centered in either left or right visual display. The annulus consisted of a sinusoidal concentric function with a radius of 23.5°.

### Experiment 3. Cue and event

This experiment was a modified version of Experiment 1 that included a spatial cue to manipulate the allocation of spatial attention. The sequence of epochs was the same as in Experiment 1, but an additional “cue” epoch was inserted after the noise epoch (0.05–0.1 s) that contained a single Gabor patch (identical to either one of the two Gabor patches during the delay epoch) that was presented on either the left- or right-hand side for 0.55 to 1.1 s. The location of the Gabor patch served as a spatial cue indicating the side where the task-relevant orientation change might occur (100% valid), but it was not informative about the occurrence or congruence of the task-irrelevant flash event. The remaining epochs proceeded in the same sequence as in Experiment 1. In change trials (50%), the cued Gabor patch changed its orientation at the onset of the change epoch. To reduce the total number of trial conditions, this experiment included only two SOAs, 150 ms and 600 ms.

Experiment 3 was run in alternating blocks of 64 left-cue trials and 64 right-cue trials during each session. The order of blocks was randomly determined at the beginning of each individual session.

## Monitoring eye movements

To measure eye movements, we used a 240-Hz charge-coupled device camera (ISCAN) in 6 head-fixed mice running Experiment 1. We used four infrared light-emitting diodes (LEDs; 940 nm) to illuminate the eye and commercially available acquisition software (ETL-200, ISCAN, Woburn, MA) to determine the center and boundary of the pupil. We then calculated eye position by subtracting the center of corneal reflection from the pupil to compensate for any translational movement of the eye at the imaging plane. To calculate pupil displacement, we converted the two-dimensional image to a rotation angle by using the estimated eyeball radius of model C57BL/6 mice (1.25 mm) (Sakatani & Isa, 2004; Stahl, 2004). To calculate eye velocity, we applied a low-pass differentiating filter to eye position traces (3-dB rolloff at 54 Hz). Saccade detection was done using a custom graphic user interface written in MATLAB script that was based on a previously published method (Krauzlis & Miles, 1996). We applied thresholds of a minimum

velocity of 150°/s, a minimum acceleration of 3000°/s<sup>2</sup>, and a minimum duration of 20 ms. All marked saccades and eye traces were manually inspected to remove any artifacts. Saccade probability was calculated as the fraction of trials within each time bin that were marked as a saccade.

## Experimental design and statistical analysis

Data were collected using eight C57BL/6J mice (four males, four females). We did not observe any systematic difference in behavioral performance between males and females in the present study. All eight mice were used for Experiments 1 and 3. Seven mice were used in Experiment 2 (four males, three females). Six mice were used for collecting eye movement data (three females and three males).

For statistical analysis, data were pooled across sessions for each mouse. Reaction times were calculated on trial outcomes defined as a hit as the first lick in the response window (200–600 ms). Hit rates and false alarm rates were calculated based on the definitions of trial outcomes. We then calculated sensitivity ( $d'$ ) and criterion based on signal detection theory (Macmillan & Creelman, 2005), where  $d' = \Phi^{-1}(H) - \Phi^{-1}(F)$ , and criterion =  $-(\Phi^{-1}(H) + \Phi^{-1}(F))/2$ , where  $\Phi^{-1}$  is the inverse of normal cumulative distribution function,  $H$  is the hit rate, and  $F$  is the false alarm rate. In the case of one mouse with  $H = 100$  and  $F = 0$ , we corrected with the equation of  $H = 1 - 1/2N$  and  $F = 1/2N$ , where  $N$  is the total number of trials for that trial type (Macmillan & Creelman, 2005).

Statistical analyses were conducted in MATLAB using the statistics and machine learning toolbox. Statistical significance was accepted as  $p < 0.05$ . Population reaction times were analyzed using a three-factor ANOVA: (1) SOA (none, 150, 250, 400, 600, or 850 ms); (2) congruency (congruent or incongruent, for trials without a stimulus event, reaction times were duplicated to be both congruent and incongruent); and (3) mouse (individual mice). The interaction between SOA and congruency were further tested, with post hoc multiple comparisons (Tukey–Kramer post hoc tests,  $\alpha = 0.05$ ).

For Experiment 1, there were 95 degrees of freedom and 35 error degrees of freedom. The SOA and Mouse factors and the SOA:Congruency, SOA:Mouse, and Congruency:Mouse interaction terms were significant:  $F(\text{SOA}) = 74.22$ ,  $p < 0.01$ ;  $F(\text{Mouse}) = 91.89$ ,  $p < 0.01$ ;  $F(\text{Congruency}) = 3.39$ ,  $p = 0.07$ ;  $F(\text{SOA:Congruency}) = 5.14$ ,  $p < 0.01$ ;  $F(\text{SOA:Mouse}) = 6.72$ ,  $p < 0.01$ ; and  $F(\text{Congruency:Mouse}) = 2.58$ ,  $p = 0.03$ .

For Experiment 2, there were 83 degrees of freedom and 30 error degrees of freedom. The SOA and Mouse factors and the SOA:Mouse interaction terms were significant:  $F(\text{SOA}) = 431.49$ ,  $p < 0.01$ ;  $F(\text{Mouse}) = 60.83$ ,  $p < 0.01$ ;  $F(\text{Congruency}) = 2.96$ ,  $p = 0.095$ ;

$F(\text{SOA}:\text{Congruency}) = 1.41, p = 0.25$ ;  $F(\text{SOA}:\text{Mouse}) = 14.73, p < 0.01$ ; and  $F(\text{Congruency}:\text{Mouse}) = 0.58, p = 0.74$ .

For Experiment 3, there were 47 degrees of freedom and 14 error degrees of freedom. The SOA and Mouse factors and SOA:Mouse interaction terms were significant:  $F(\text{SOA}) = 66.32, p < 0.01$ ;  $F(\text{Mouse}) = 50.39, p < 0.01$ ;  $F(\text{Congruency}) = 0.19, p = 0.67$ ;  $F(\text{SOA}:\text{Congruency}) = 2.37, p = 0.13$ ;  $F(\text{SOA}:\text{Mouse}) = 3.64, p = 0.01$ ; and  $F(\text{Congruency}:\text{Mouse}) = 2.59, p = 0.06$ .

One-way ANOVAs were used to assess the difference in hit rates, false alarm rates,  $d'$ , and criteria across all trial types for population data. This was implemented by creating a “trial type” factor, which combined all levels of SOA and congruency; for example, for Experiment 1 there were 11 types of trials (five levels of SOA times two of congruency plus the baseline condition). Tukey–Kramer post hoc tests were used when appropriate, specifically to compare each trial type to the baseline condition ( $\alpha = 0.05$ ). Chi-square tests were performed to compare the within-subject effects on hit rates and false alarms by comparing the baseline condition without a flash event to each trial type with a flash event. To calculate within-subject effects on  $d'$  and the criterion, we calculated the median  $d'$  and criterion for each mouse and generated 95% confidence intervals (CIs) with bootstrapped resampling for each trial type. Significant effects were defined as non-overlap between the 95% CI for the no-stimulus condition and each trial type with a flash event.

Wilcoxon signed-rank tests were used to compare the mean saccade probability from 0 to 400 ms after the stimulus-event onset between trials with a flash event on the same side as the eye being recorded (ipsilateral flash event) and two controls, a flash on the opposite side of the eye being recorded (contralateral flash event) and a no-flash event. Data from trials with a flash event were only included from the timing of the flash onset to the onset of the orientation change to prevent any eye movements related to the orientation change or collecting reward from being included.

## Code accessibility

Data were collected and processed using custom scripts written in MATLAB. Upon reasonable request, MATLAB code and data supporting the findings of this study will be made available from the corresponding authors.

## Results

In each experiment, head-fixed mice viewed a pair of visual displays centered on the right or left visual field

while running on a polystyrene wheel. All experiments progressed through trial epochs following the temporal structure outlined in Figure 2A. On change trials, mice had to lick a center spout during a 600-ms window starting 200 ms after the orientation change in order to be counted as a hit and receive a reward. The change event was equally likely to occur on the left or right side of the display, and these conditions were randomly interleaved within each block of trials. On no-change trials, mice had to withhold from licking during the response window; on these trials, if the first contact with the lickspout in the change epoch occurred within the response window, it was counted as a false alarm. To test stimulus-driven attention and the presence of inhibition of return in mice, on randomly interleaved trials we included a task-irrelevant stimulus event (referred to as flash event in Experiments 1 and 3 or as annulus event in Experiment 2) at variable times (SOAs) before the orientation change. The flash event could occur either on the same side of the visual display as the orientation change (congruent) or the opposite side (incongruent). As described in the following sections, we found that flash events systematically shortened reaction times with no reduction in response accuracy, but we found no evidence for inhibition of return.

## Stimulus-driven improvements in detection performance in mice

To provide a stimulus event similar to the brief and salient events often used in studies with human subjects (Posner & Cohen, 1984) we briefly increased the brightness of one of the two Gabor patches on randomly interleaved trials (Figure 2A). We compared change-detection performance on trials with either a spatially congruent or incongruent flash event at different SOAs to baseline performance in time-matched trials without a flash event. Data were collected from a cohort of eight mice trained to detect a 12° orientation change. Each animal was run in this experiment for nine to 16 consecutive sessions, averaging 475 trials a day until we had obtained at least 100 repeats of each trial type.

Flash events decreased reaction times across SOAs for both congruent and incongruent events (Figure 3A). Without a flash event, the median reaction time across mice was  $397.9 \pm 32.3$  ms. With a flash event, median reaction times decreased by 35 to 60ms, and large reductions in reaction times emerged with SOAs of 250 and 400 ms but leveled off with longer SOAs. A three-way ANOVA revealed that, with the exception of congruent flash events at the shortest SOA, reaction times were shorter across all SOAs and spatial congruencies compared with the baseline no-flash condition (post hoc  $p < 0.01$ ). This pattern was more consistently observed for individual mice at longer

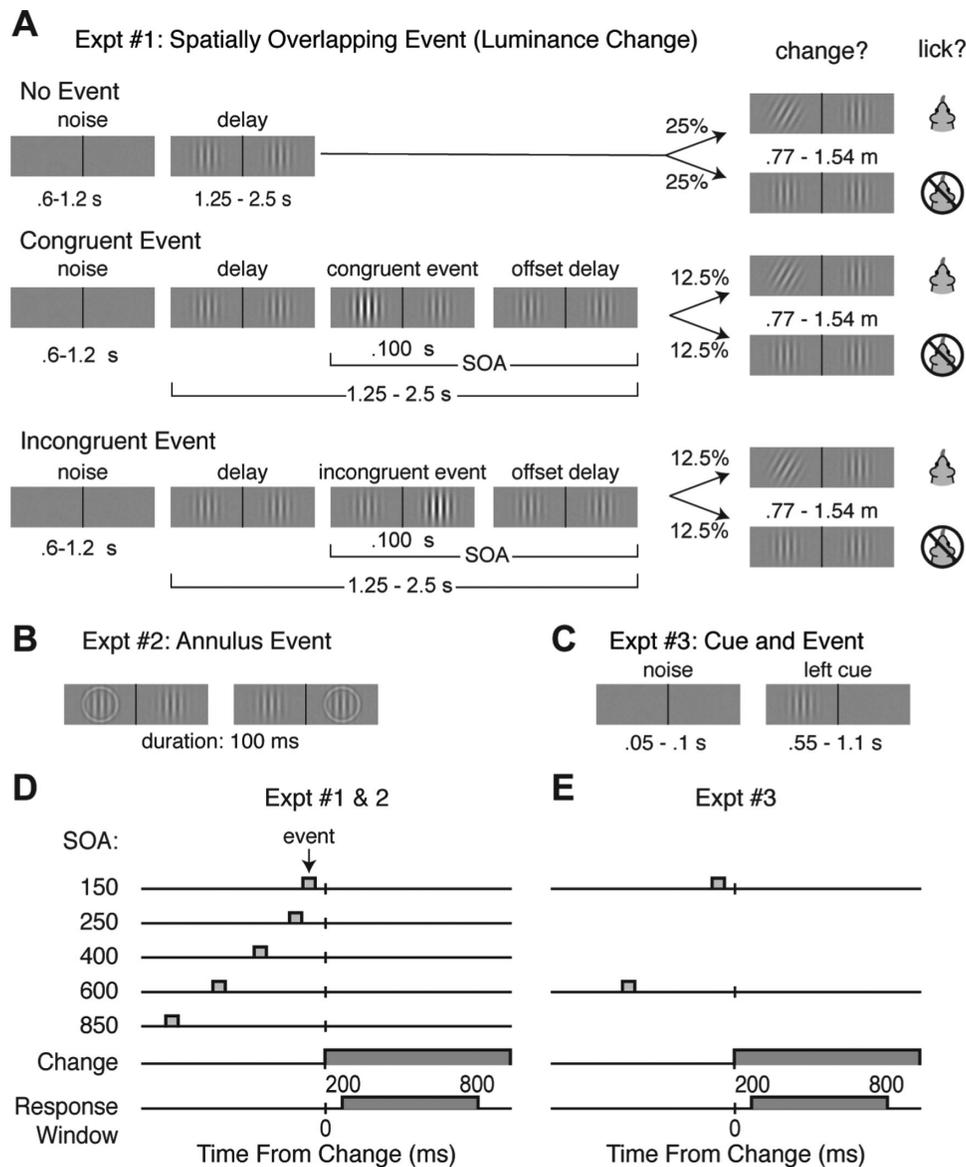


Figure 2. Stimulus-driven visual detection task. (A) Screen shots from the three different trial types included in Experiment 1: no event (top), congruent event (middle), and incongruent event (bottom). The sequence of screen shots with timing and/or distances associated with each are depicted, as well as the probabilities of each test epoch and the definition of a correct response for each outcome (Lick?). (B) Examples of the annulus event used in Experiment 2, illustrating the stimulus event presented during left event and right event trials. (C) Schematic of the first two epochs in trials in Experiment 3, depicting a left-cue block. (D, E) Timeline of stimulus events, test epochs, and response windows in Experiments 1 and 2 (D) and in Experiment 3 (E). Trial outcomes were defined based on a 600-ms response window for licks, which started 200 ms after the orientation change; extraneous licks during the delay period aborted trials, but extraneous licks after the stimulus events but before the response window were not penalized.

SOAs. For flash events with longer SOAs (400, 600, and 850 ms), the majority of mice (five of eight) had faster reaction times compared with the no-flash condition (two-way ANOVA,  $p < 0.05$  on individual mice).

Although the flash event consistently reduced reaction times, it did not matter whether the flash event was on the same side or opposite side as the subsequent change in orientation. If mice exhibited inhibition of return in this experiment, we would have

expected to see differences in reaction times at longer SOAs depending on the congruency of the flash event (i.e., longer reaction times for congruent compared with incongruent flash events). Instead, we found no difference, despite the overall large reductions in reaction times. Specifically, reaction times for SOAs of 250, 400, 600, and 850 ms did not differ based on the congruency of the flash event (three-way ANOVA, post hoc 250 SOA,  $p = 0.97$ ; 400 SOA,  $p = 1.0$ ; 600 SOA,

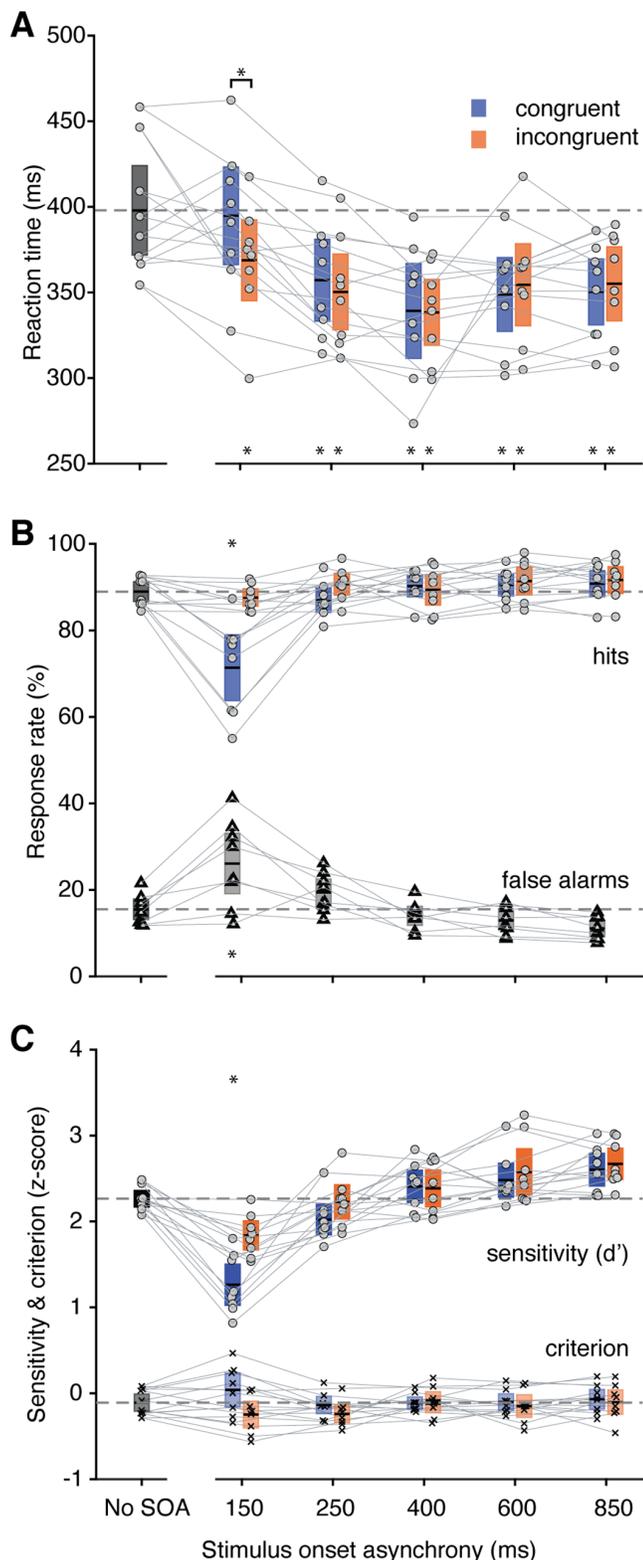


Figure 3. In Experiment 1, stimulus events decreased reaction times without reducing detection accuracy. (A) Reaction times for mice ( $n = 8$ ) in Experiment 1 across different SOAs and congruencies. Open circles plot the median reaction times of individual mice, and gray lines represent individual mice across SOAs. Black horizontal bars indicate population means of medians; shaded boxes indicate 95% CIs of the mean for no

$p = 0.99$ ; 850 SOA,  $p = 1.0$ ). This was consistent in all mice individually, as well; no mouse showed a difference in reaction times between congruent and incongruent flash locations for SOAs of 250 ms or longer.

The faster reaction times seen in trials with a flash event were not due to changes in the speed–accuracy tradeoff in the behavior of our mice: flash events reduced reaction times without reducing the accuracy of detection performance. Without a flash event, mice on average had a high hit rate,  $88.9\% \pm 2.3\%$ , and a low false alarm rate,  $15.5\% \pm 2.4\%$ . With a flash event, mice maintained high hit rates ( $>80\%$ ) and low false alarm rates ( $<20\%$ ), despite the faster reaction times. A one-way ANOVA analysis of hit rates across all trial types revealed that only the shortest congruent SOA (150 ms) resulted in lower hit rates than the no-flash event baseline condition (post hoc  $p < 0.01$ ). Similarly, a one-way ANOVA analysis of false alarm rates revealed that, again, only the shortest SOA produced higher false alarm rates than the baseline condition (post hoc  $p < 0.01$ ). A similar pattern was observed for individual mice at longer SOAs. All mice showed comparable or higher hit rates at all longer SOAs (400, 600, and 850 ms) for either spatial congruencies compared with the no-flash event. Additionally, all mice had comparable or lower false alarm rates for each of these three SOAs compared with the baseline condition.

To summarize these effects on performance accuracy, we applied signal detection theory to convert the hit and false alarm rates into measures of perceptual sensitivity ( $d'$ ) and response criterion ( $c$ ). This analysis revealed no change in criterion and some variable effects on sensitivity (Figure 3C). A one-way ANOVA analysis of sensitivity revealed that a congruent flash at the shortest SOA resulted in lower sensitivity compared with no-flash trials (post hoc  $p < 0.01$ ), whereas no other SOA or congruency condition differed from

← stimulus event (gray), congruent stimulus event (blue), and incongruent stimulus event (orange) trials across five SOAs. The dashed gray line indicates the population mean reaction time for no flash event. Asterisks (\*) indicate conditions with values significantly different from those in the baseline condition. (B) Hit rates and false alarm rates. Triangles show mean false alarm rates for individual mice and do not have a congruency. Gray-shaded boxes indicate 95% CIs of the mean false alarm rates for no flash event (dark gray) and five SOAs (light gray). Asterisks (\*) apply to hits when above the data and to false alarms when below. All other conventions are the same as in panel A. (C) Detection sensitivity ( $d'$ ) and criterion across mice. The “x” labels indicate the mean criterion for individual mice for all trial types. Asterisks (\*) apply to sensitivity when above the data and to criterion when below. All other conventions are the same as in panel A. →

no-flash trials. Additionally, the response criterion did not differ across any of the trial types (one-way ANOVA  $p = 0.17$ ). This pattern was also consistent for mice individually. The majority of mice (six of eight) had comparable or higher sensitivity for each SOA except the shortest (150 ms) when compared with the no-flash event. Similarly, for each SOA and congruency, half of the mice (four of eight) had a similar criterion compared with the no-flash trials. These results confirm that the stimulus-driven reductions in reaction times induced by the flash event were not accompanied by reductions in perceptual sensitivity or shifts in the response criterion.

Overall, these results show that a flash event markedly reduced the reaction times of mice in our visual detection task, with the full reduction emerging 250 to 400 ms after the flash, consistent with stimulus-driven shifts of attention. However, we observed no difference in the changes in reaction times between congruent and incongruent flash events, indicating that there was no evidence for inhibition of return. These effects cannot be explained by changes in the speed–accuracy tradeoff for our mice, because the accuracy of performance at these shorter reaction times was just as good as that observed in the no-flash baseline condition.

Although the pattern of results was consistent at longer SOAs, one exception to this overall pattern was the performance for the congruent flash at the shortest SOA (150 ms), which resulted in slower reaction times compared with the incongruent flash condition (three-way ANOVA, post hoc  $p < 0.01$ ), and a reduction in hit rates and sensitivity compared to the no-flash condition (one-way ANOVA, post hoc  $p < 0.01$ ). We suspected that such outlier effects might be due to visual masking, because the flash was implemented as a brightening of the same Gabor stimulus required for the visual change detection. To test this possibility, we repeated the experiments using an annulus stimulus event intended to minimize local visual masking.

### Annulus event also evokes stimulus-driven attention in a spatially nonspecific manner

Experiment 2 was identical to Experiment 1, except that the stimulus event was an annulus (Figure 2B) that surrounded but did not retinotopically overlap with the Gabor patch, rather than a brightening of the Gabor patch itself. Data were collected from a cohort of seven mice trained to detect a  $12^\circ$  orientation change.

Reaction times were faster in trials with an annulus event compared with trials without an annulus event at all SOAs (Figure 4A). Trials without an annulus event had a median reaction time of  $394.3 \pm 29.6$  ms, whereas trials with an annulus event had reaction times

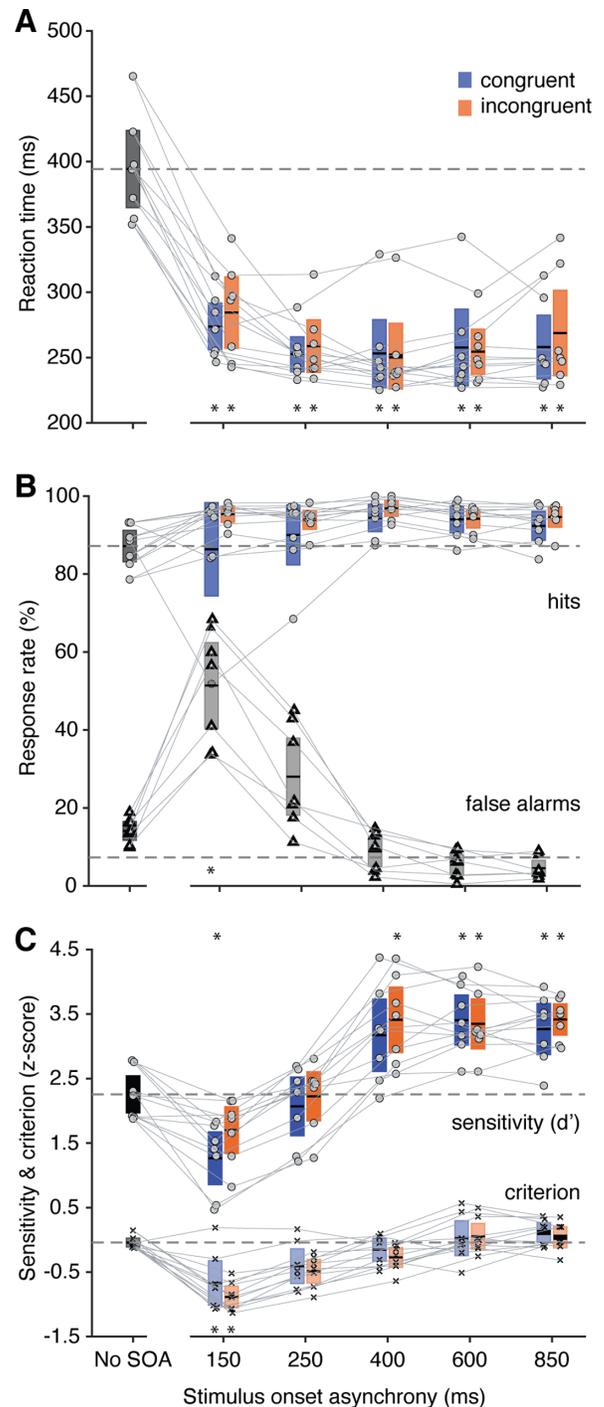


Figure 4. In Experiment 2, mice showed stimulus-driven effects in a non-spatially specific manner. (A) Reaction times for mice ( $n = 7$ ) in Experiment 2 across different SOAs and congruencies. All other conventions for panels A to C are the same as in Figure 3.

over 100 ms faster than trials without the annulus event. A three-way ANOVA revealed that, across all SOAs, mice had faster reaction times with an annulus event compared with the baseline condition (post hoc

$p < 0.01$ ); this was consistent across all mice (two-way ANOVA  $p < 0.05$ ).

The effect of the annulus event on reaction times did not depend on whether the annulus was spatially congruent or incongruent with the orientation change. Across all SOAs, reaction times did not differ based on the congruency of the annulus event; for three-way ANOVA,  $F(\text{SOA}:\text{Congruency}) = 1.41$ ,  $p = 0.25$ . This pattern was consistent across individual mice. All mice showed no difference in reaction times between congruent and incongruent annulus events.

Despite the large reductions in reaction times produced by the annulus event, mouse detection performance was again just as good with an annulus event as without an annulus event at longer SOAs (Figure 4B). In no-annulus event trials, mice showed high hit rates ( $87.2\% \pm 4.0\%$ ) and low false alarm rates ( $14.1\% \pm 2.4\%$ ). With an annulus event, hit rates were similarly high ( $>80\%$ ), and false alarm rates remained relatively low ( $<20\%$ ). Hit rates did not differ across any trial types (one-way ANOVA  $p = 0.1$ ). A one-way ANOVA analysis of false alarm rates revealed that only the shortest SOAs (150 ms) had higher false alarm rates than the baseline condition (post hoc  $p < 0.01$ ). Individual mice showed similar effects. Five of seven mice had comparable or higher hit rates for each SOA in trials with an annulus event compared with trials without an annulus event. All mice showed similar or lower false alarm rates in trials with SOAs of 400 ms or longer compared with trials without an annulus event.

We again applied signal detection theory and found that mice had an increase in sensitivity for longer SOAs and no significant difference in criterion compared to the baseline condition at long SOAs (Figure 4C). A one-way ANOVA analysis of sensitivity revealed that sensitivity was higher for SOAs of 400, 600, and 850 ms incongruent and 600 and 850 ms congruent compared with the baseline condition (post hoc  $p < 0.05$ ). Additionally, sensitivity for the shortest SOA congruent was lower than the baseline condition (one-way ANOVA, post hoc  $p < 0.05$ ). Sensitivity for all other trial types did not differ compared with no-annulus event trials. A one-way ANOVA analysis of the criterion found that the criterion was only lower for the shortest SOA (150 ms), regardless of congruency, compared with the baseline condition (post hoc  $p < 0.01$ ). This was largely driven by an increase in false alarm rates for the shortest SOA, as the hit rate did not differ across trial types. Individual mice had similar results that were more consistent at long SOAs. For SOAs of 400 ms and longer, all mice had comparable or higher sensitivity in trials with an annulus event compared with trials without an annulus event. Additionally, for these same SOAs, three of seven mice showed no difference in the criterion for each SOA and congruency between trials with and without an annulus event.

To summarize, mice had faster reaction times in trials with an annulus event compared with trials without an annulus event at all SOAs. We can again rule out a speed-accuracy tradeoff, because at longer SOAs perceptual sensitivity was similar or higher and the criterion was similar in trials with and without an annulus event. These results provide evidence that the annulus event evoked a form of stimulus-driven attention, although three important features of this stimulus-driven effect should be noted. First, the effect of the annulus event in reducing reaction times was not spatially specific, as similar reductions were found for both spatially congruent and incongruent annulus events. Unlike in Experiment 1, this was true even at the shortest SOA (150 ms), which provides evidence for a possible masking effect by the flash event. However, there was a bias toward licking at the shortest SOA (150 ms) as seen in an increase in false alarms and a decrease in the criterion. Second, at long SOAs (600 and 850 ms) perceptual sensitivity increased compared with the baseline condition, regardless of congruency. Finally, we again did not find evidence for inhibition of return—there were similar reductions in reaction times for long SOAs regardless of whether or not the annulus was spatially congruent or incongruent with the subsequent orientation change.

One possible explanation for the lack of spatial specificity and the absence of inhibition of return is that these spatial effects might depend on the voluntary allocation of visual spatial attention. In Experiments 1 and 2, we purposely did not provide spatial cues to the mice in order to isolate the possible stimulus-driven effects. However, the presence of spatially specific stimulus-driven effects might require animals to voluntarily allocate spatial attention when they perform the task. To test this, we ran an additional set of experiments in which we provided a spatially specific cue at the beginning of the trial and measured stimulus-driven effects in these experiments.

### No evidence of inhibition of return even when spatial cueing is available to mice

In Experiment 3, mice were given spatial cues about the location of the possible orientation change, following a previously established task design (Krauzlis & Wang, 2018). Briefly, spatial cueing was introduced by using blocks of 64 trials in which the orientation change occurred (50% probability) on only one side of the visual display (left or right), indicated at the start of each trial by a spatial cue (Figure 2C). Aside from the addition of spatial cues on interleaved blocks, the trials progressed through the same epochs as Experiment 1. Given the consistency of the SOA effects in Experiments 1 and 2 and to economize on the number of conditions,

we tested the effects of a flash event using two different timings: a short (150 ms) and a long (600 ms) SOA. These two SOAs were chosen based on the timing of exogenous attention in humans and SOAs previously used in rodent studies (Marote & Xavier, 2011; Müller & Rabbitt, 1989). Data were collected from eight mice trained to detect a 12° orientation change.

Consistent with the results from the other experiments, flash events decreased reaction times for the longer SOA (Figure 5A). With no flash event, the median reaction time for cued trials was  $422.4 \pm 41.2$  ms, whereas with a flash event the median reaction times were reduced to 325 to 400 ms. The reaction times were significantly faster than the baseline condition for the longer SOA (600 ms) but not for the shorter SOA (150 ms) condition (three-way ANOVA, post hoc  $p < 0.01$ ). This effect was consistent among individual mice; all mice had faster reaction times at the longer SOA compared with the baseline condition (two-way ANOVA  $p < 0.05$ ). The effects on reaction time did not depend on whether the flash event occurred on the same or opposite side as the cued orientation change. The reaction times for congruent and incongruent trials did not significantly differ for either the short SOA or the long SOA; for three-way ANOVA,  $F(\text{SOA}:\text{Congruency}) = 2.37$ ,  $p = 0.13$ . Among individual mice, for the longer SOA all eight mice had similar reaction times for congruent and incongruent flash event trials. Therefore, even in the presence of a spatial cue that produced significant changes in reaction times, we did not find evidence for inhibition of return.

Performance accuracy also did not depend on the spatial congruency of the flash event. The hit rates in trials with congruent and incongruent flash events at the long SOA were not significantly different from each other and also were not different from the hit rates in the baseline no-flash condition (one-way ANOVA, post hoc, all comparisons  $p > 0.78$ ) (Figure 5B). Similarly, applying signal detection theory to take false alarms into account, a one-way ANOVA revealed that the criterion did not differ in trials with a flash event compared with the baseline no-flash condition, nor did the criterion differ based on the congruency of the flash event (post hoc  $p = 0.18$ ) (Figure 5C). Additionally, sensitivity at the long SOA was unchanged from the no-flash condition and did not differ based on the spatial congruency of the flash event (one-way ANOVA, post hoc, all comparisons  $p > 0.19$ ) (Figure 5C). Thus, the accuracy of performance also did not show evidence of inhibition of return.

In summary, mice that showed evidence of using spatial cues had faster reaction times and comparable accuracy in trials with a flash event compared with trials without a flash event at the long SOA. These results, which are similar to those in the previous experiments, show that mice do not display behavioral performance consistent with inhibition of return at longer SOAs, even when the mice are verified to utilize a spatial cue.

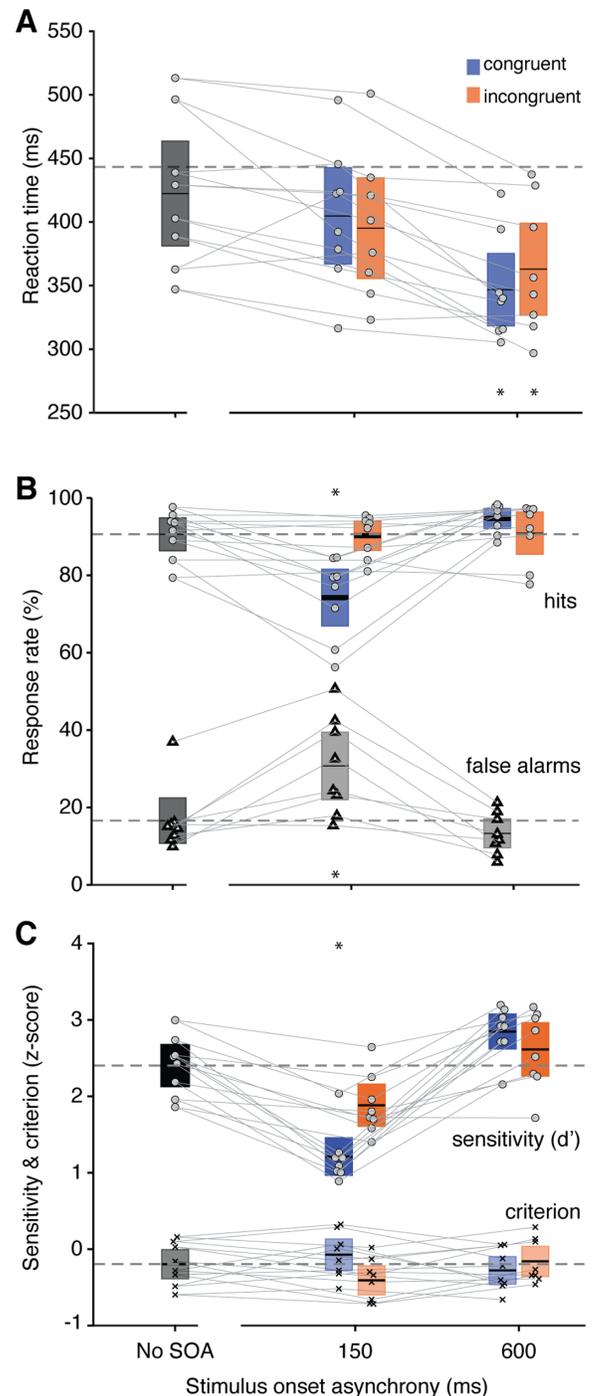


Figure 5. In Experiment 3, mice were provided with spatial cues but did not show evidence for inhibition of return. (A) Reaction times in Experiment 3 ( $n = 8$ ) across two SOAs and congruencies. All other conventions for panels A to C are the same as in Figure 3.

### Flash events do not lead to an increase in saccades

An additional concern was that the flash event might evoke saccades, causing systematic shifts of the retinal image that could lead to the observed behavioral

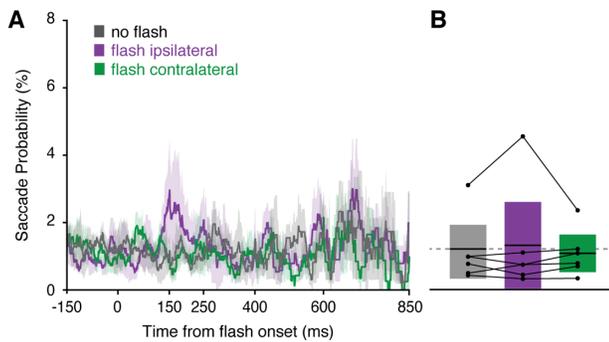


Figure 6. Flash events did not significantly alter saccade probability. (A) Population average ( $n = 6$ ) of saccade probability plotted in 1-ms time bins aligned to flash onset for trials with no flash (dark gray) and flashes ipsilateral (purple) or contralateral (green) to the recorded eye. Data were collected using Experiment 1. Colored shaded regions indicate  $\pm 1$  SEM. (B) Mean saccade probability from 0 to 400 ms after flash onset for each trial type. Circles represent means for individual mice and are connected by a line for each trial type. Shaded regions indicate  $\pm 1$  SEM. For comparison, the gray dashed line shows the mean saccade probability for the no-flash condition.

changes. To address this, we recorded eye position in a subset of six mice while running the behavioral task in Experiment 1. Because we wanted to test whether the flash event caused saccades, we compared trials with a flash event that occurred on the same side as the recorded eye (ipsilateral) to two control conditions: trials with a flash occurring on the opposite side as the recorded eye (contralateral) and trials with no-flash event. In trials with a flash event, we looked at all SOAs aligned to the onset of the flash event (Figure 6A). In trials without a flash event, we pseudorandomly aligned these trials to an SOA within each block. Overall, the probability of saccades after the flash was extremely low, less than 5% across all trial types, even for the one mouse that exhibited slightly more saccades for ipsilateral flashes (Figure 6B). In order to quantify this, we calculated the saccade probability over a time course matched to the stimulus-driven changes in attention, 0 to 400 ms after the stimulus onset. Saccade probability did not significantly differ between trials with a flash ipsilateral to the recorded eye and either of the two control conditions (Wilcoxon signed rank, no-flash  $p = 0.84$ ; contralateral  $p = 0.44$ ) (Figure 6B). We conclude that the behavioral effects of the flash on task performance were not due to changes in saccadic eye movements.

## Discussion

This study examined the presence and time-course of stimulus-driven attention in head-fixed mice. Our

results show that task-irrelevant, salient stimuli can capture covert attention in mice performing a visual detection task. Mice had faster reaction times and uncompromised detection accuracy in trials with a stimulus event compared with trials without a stimulus event. This reduction in reaction time unfolded over several hundred milliseconds, comparable to that in humans. However, mice did not exhibit inhibition of return, even when they used spatial cues. These results expand on the research exploring covert attention in mice and establish the mouse as a model to study the neuronal mechanisms of stimulus-driven attention.

## Stimulus-driven attention in rodents

Current knowledge of stimulus-driven attention in rodents comes largely from studies involving nose-poke tasks. Wagner et al. (2014) explored stimulus-driven attention in rats and found that spatially uninformative events enhance performance. Rats were faster to nose-poke toward targets as the delay between the stimulus and target increased, regardless of congruency. Recently, You and Mysore (You & Mysore, 2020) studied stimulus-driven attention in mice and found that distractors hinder performance. Mice learned to discriminate between vertical and horizontal gratings and nose-poked to the corresponding left or right port. When a distractor with conflicting information was simultaneously presented, mice were slower to nose-poke and responded to the incorrect port more than when there was no distractor, but only when the distractor was more salient than the target.

We used head-fixed mice to ensure that the behavioral effects seen were due to changes in visual perception. In particular, we had precise temporal and spatial control over the visual stimulation, comparable with primate studies. By measuring eye movements, we were able to determine that our effects were due to changes in attention, rather than caused by saccades. Further, our mice reported an orientation change on either side by licking a central spout, which minimized confounding effects of lateralized motor biases or differences in orienting. Because of the precise control of the visual stimuli and the lack of orienting movements, we were able to attribute the stimulus-driven effects in behavioral performance to changes in the allocation of covert visual attention.

## Temporal and spatial aspects of stimulus-driven attention in rodents

Spatial selective attention is often considered in two broad forms: endogenous and exogenous. Endogenous

attention is defined as voluntary and oriented toward task-relevant stimuli, whereas exogenous attention is described as being involuntary and captured by salient stimuli (Posner & Cohen, 1984). These two forms of attention are often considered to be the products of different control mechanisms (Corbetta & Shulman, 2002).

Our results provide new insight into how these forms of attention operate in mice. A distinctive feature of stimulus-driven attention is the temporal profile of the changes in performance. In humans, macaques, and rats, stimulus-driven attention emerges over a time course of ~100 to 300 ms (Bowman et al., 1993; Marote & Xavier, 2011; Müller & Rabbitt, 1989). Similarly, our results show that, in mice, stimulus-driven changes in attention are evident ~150 to 400 ms after the stimulus event. Thus, in mice and other species, salient stimuli cause changes in the allocation of attention that takes a few hundred milliseconds to fully develop.

In contrast to the conserved time course of stimulus-driven effects, the spatial specificity is more variable across species. In our experiments, mice exhibited reductions in reaction times in trials with a stimulus event regardless of congruency and showed no evidence for inhibition of return. Our findings are in line with previous research that did not find consistent evidence for inhibition of return in rats (Wagner et al., 2014; Weese et al., 1999). These results differ from those found in primates, birds, and fish, where there is evidence for inhibition of return (Dorris, Taylor, Klein, & Munoz, 1999; Gabay et al., 2013; Lev-Ari et al., 2020). This difference cannot be attributed to an absence of allocating spatial attention in mice, because a portion of our mice showed spatial cuing effects and still did not show inhibition of return. Instead, the lack of spatial specificity we observed may be due to the way that mice used the visual stimulus events in our task and how endogenous and exogenous forms of attention may interact in different contexts.

To clarify this, there is evidence that separating attention into these two distinct forms is an oversimplification (Folk, Remington, & Johnston, 1992; Theeuwes, 1991; Vossel, Geng, & Fink, 2014). Instead, one theory is that the likelihood that stimuli will capture attention depends on their relevance to the task. Specifically, exogenous attention is usually captured by stimuli with features similar to the endogenously attended target. For example, a stimulus with an abrupt onset may capture attention when the target is also an abrupt onset but may not affect performance when the target is a distinct color (Folk et al., 1992). This was explained as “attentional control settings” in which task goals determine which category of stimulus features are important, resulting in the rapid capture of attention by stimuli from that category, even when the stimulus itself is irrelevant (Folk et al., 1992).

Attentional control settings can help explain our results. The target that the mouse detected in our experiment was an abrupt orientation change. Similarly, the stimulus event was an abrupt onset of either a flash or an annulus. This resemblance in visual “abruptness” between the target and the stimulus onset may explain the stimulus-driven changes in attention we observed. The absence of inhibition of return requires an additional assumption—that the attentional control settings of our mice emphasized abruptness but not spatial location. The stimulus events in our experiments were intentionally not informative about target location to prevent the recruitment of endogenous effects, so mice had no incentive to associate the stimulus event with the target location. Consequently, the lack of spatial specificity in our stimulus-driven changes of attention is consistent with control settings that processed the stimulus event as an alerting signal (Posner, 1980), similar to that seen in primates and rodents (Fecteau & Munoz, 2007; Hamame, Delano, & Robles, 2008; Witte, Villareal, & Marrocco, 1996). A related possibility is that the mice might have used the occurrence of the stimulus event to reduce the uncertainty about the timing of the orientation change, even though the stimulus event was uninformative about where the orientation change would occur. Thus, the stimulus-driven changes in attention of our mice may have been different from the classic effects, but they were entirely consistent with the limited information that could be extracted from the occurrence of the stimulus event in our task.

These considerations about the possible attentional control settings deployed in our task imply that, under different task conditions and control settings, mice could exhibit spatially specific stimulus-driven effects. Under what conditions might these be evident? Mice might require special training to adopt control settings that include the location of visual stimuli, which could reflect ethological differences in the use of sensory inputs. Inhibition of return has been found primarily in animals that have complex visual systems that are relied upon for catching prey. In fact, inhibition of return is thought to be a foraging facilitator, promoting orienting toward new visual items (Klein & MacInnes, 1999). In contrast, mice rely on vision for innate, defensive behaviors, such as avoiding potentially dangerous stimuli (Yilmaz & Meister, 2013), but primarily use other sensory modalities, such as touch and smell, during foraging (Gire, Kapoor, Arrighi-Allisan, Seminara, & Murthy, 2016). Additionally, rodents favor tactile over visual cues during exploratory behavior (Clark, Hamilton, & Whishaw, 2006; Schiffman, Lore, Passafiume, & Neeb, 1970). Consequently, mice might be more likely to exhibit inhibition of return while using sensory modalities that are more consistent with foraging

behavior, such as whisking (Deschênes, Moore, & Kleinfeld, 2012). However, mice use vision when hunting in an illuminated open field (Hoy, Yavorska, Wehr, & Niell, 2016), so we cannot rule out that mice might show inhibition of return in other contexts, especially if the visual events were useful for guiding spatially organized behaviors.

## Neuronal mechanisms of attention in mice

The mouse visual system has been intensively studied, and several areas in the mouse brain have been identified as potentially involved in visual attention. These include areas traditionally studied in vision, such as the primary visual cortex and the superior colliculus, which are critical in perceptual decision making (Hu, Kamigaki, Zhang, Zhang, Dan, & Dan, 2019; Lee, Tran, Turan, & Meister, 2020; Resulaj, Ruediger, Olsen, & Scanziani, 2018; Speed, Rosario, Mikail, & Haider, 2020; Wang, McAlonan, Goldstein, Gerfen, & Krauzlis, 2020). Additionally, areas associated with attention in other animals have been shown to be important in orienting in mice. These include the dorsal anterior cingulate cortex, which is involved in sustained attention (Koike, Demars, Short, Nabel, Akbarian, Baxter, & Morishita, 2016), and the medial dorsal thalamus, which plays a role in cross-modal selection (Rikhye, Gilra, & Halassa, 2018). Having demonstrated that mice exhibit stimulus-driven attention, our results show that mice can be used to better understand how early visual processing and cortical areas interact to respond to task-irrelevant stimuli.

## Conclusion

Our study demonstrates that salient stimulus events can drive covert visual attention in mice. The main effect, which was a reduction in reaction times in trials with a stimulus event compared with trials without a stimulus event, unfolded over a time course that is comparable to that seen in other animals. However, these effects were not spatially specific, as mice had similar behavioral performance whether the targets were spatially congruent or incongruent with the preceding stimulus event. These results highlight the importance of covert attention in mice and expand on the similarities and differences seen in exogenous attention in rodents and other animals. Together with our recent work, our findings validate the mouse as an animal model to explore the neuronal mechanisms of stimulus-driven attention.

*Keywords:* visual attention, mouse, inhibition of return

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