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Human vision maintains a rich representation of objects moving behind an occluder

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Vision may seem continuous, but it is frequently disrupted, by internal processes, such as blinks and fast eye-movements, and by external foreground clutter obscuring background objects. Yet when a bicycle passes behind a bush, we maintain a strong sense that it has not vanished, but persists, continuing its unseen motion. Using an indirect probe technique, we show that the visual system maintains, for at least 1 s, a rich perceptual representation of objects moving behind occluders. We created the impression of two disks moving behind a visible occluder, and after 1 s participants judged the colour of a probe disk flashed briefly between their virtual trajectories. The perceived colour of the test was strongly biased towards that of the inducers, showing *colour assimilation*. Our results show that the visual system maintains, at an early perceptual level, a relatively rich representation of temporally occluded objects, mapping their spatio-temporal trajectories, and storing information about sensory properties such as colour.

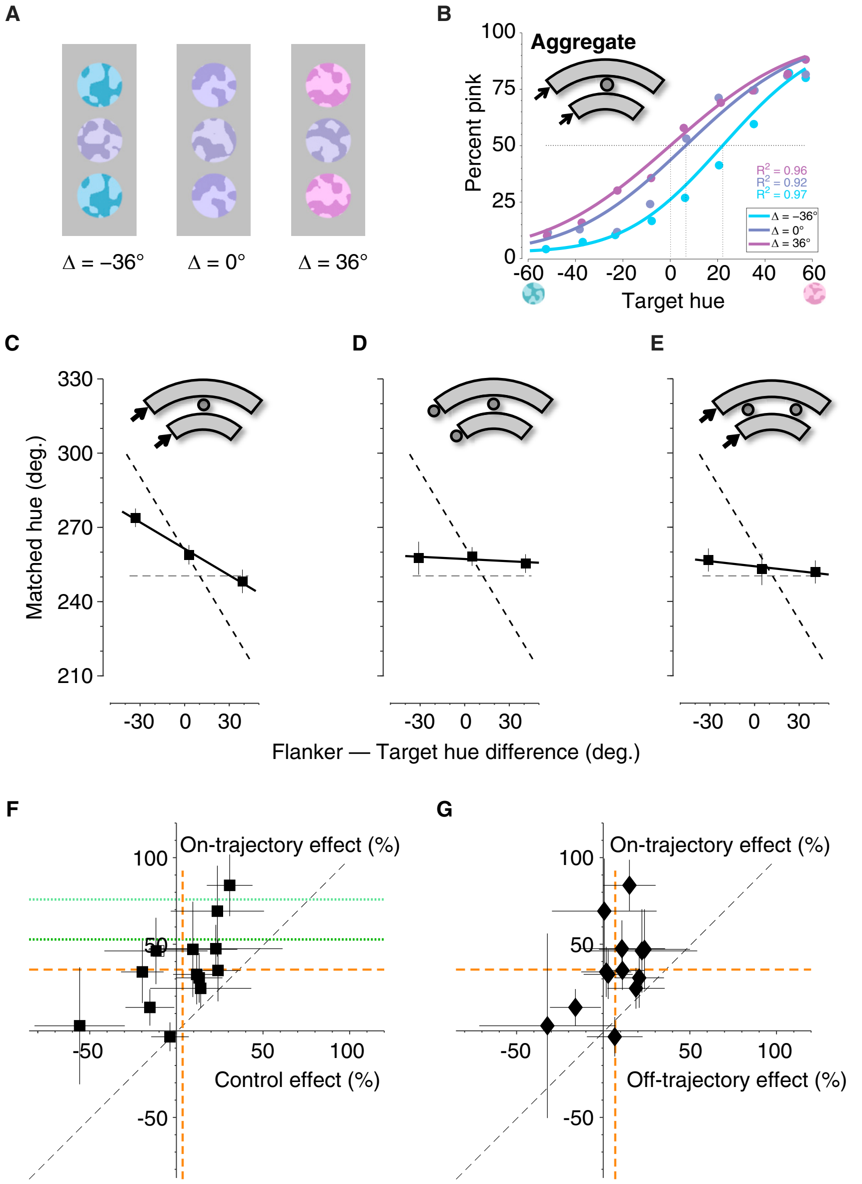

Figure 1. Main results of interpolation experiment.
(A) Examples of target patches flanked by inducers, either greener (left), identical (centre) or pinker (right) than the target colour. (B) Psychometric functions for the 'aggregate observer' (data pooled from all participants) for on-trajectory probes. The curves plot percent 'pink' responses as a function of target colour (in DKL colour space) separately for greener (−36°), identical (0°) and pinker inducers (+36°). The data are well fit by Gaussian error functions, whose median (50%) estimates the matched colour (point of subjective equality: PSE). (C–E) Matched colour (PSE) as function of relative inducer colour for the on-trajectory motion (C), stopped (D) and off-trajectory conditions (E). Symbols show mean PSEs with S.E.M.s, and continuous lines the best linear fit. On- and off-trajectory trials were interleaved within the same session. (F,G) Strength of the effect (slope of the fitted lines in panels C and E), comparing the on-trajectory position with the stopped (F) and off-trajectory (G) conditions. Error bars are bootstrapped S.E.M.s from individual psychometric functions. Orange lines show mean effects, green lines the average effects for static flankers[1]: low target saturation (light green 76%) and high target saturation (dark green 53%).

The experimental setup is illustrated in Figure S1 and Video S1 (Supplemental information). Observers fixated the small dark grey dot for the duration of the trial. Two disks (Figure 1A) moved along an arc trajectory, then passed behind a black occluder to reappear the other side 2 s later. Observers judged whether a target probe flashed briefly between the trajectories of the occluded disks appeared greener or pinker than a remembered standard. Figure 1B plots the proportion of trials when the target appeared pinker than the standard, against target hue, separately for the three different inducer hues illustrated in Figure 1A. The individual psychometric functions for each observer (Figure S2) yield estimates of matched colour (Points of Subjective Equality: PSEs), which are plotted as a function of the relative inducer colour in Figure 1C. On average, pinker inducers (Δ = +36° in DKL colour space) decreased the average PSE while greener inducers (Δ = −36°) increased it, showing assimilative dependence on relative inducer colour. The slope of the linear fit of the PSEs quantifies the weight of the inducers on the perception of the target colour (zero, no effect; –0.5 equal contribution of inducer and physical target colour; and –1 total dominance of the inducer). The best fit to the data had average slope of –0.36 (95% CIs: [–0.71, –0.01]), significantly different from zero ($t(12) = 5.29$, $p < 0.001$, $BF_{10} = 163$), showing that the occluded inducers contribute to 36% of the perceived target colour. This is less than that obtained with physically present stationary inducers[1] (dotted green lines in Figure 1F,G) but remains a strong and significant effect.

To show that the effect was specific to occluded motion, we ran two control conditions. In one, the inducers stopped dead before the occluder, rather than slipping under it. The best-fitting slope of the group-mean PSEs against inducer–target colour differences (Figure 1D) was –0.03 [–0.43 0.37], not significantly different from zero ($t(12) = 0.50$, $p = 0.63$), with Bayes factor (BF_{10}) = 0.31, substantial evidence that the inducers had no effect. We also measured assimilation for targets flashed off the inducer trajectories. Off-trajectory inducers had no measurable effect on perceived colour, with slope of –0.07 [–0.47, 0.34], implying 7% colour assimilation, not statistically significant ($t(12) = 1.49$, $p = 0.16$, $BF_{10} = 0.68$).

Figure 1F and 1G show individual data for all observers, comparing the magnitude of colour assimilation for the motion condition with the stopped and off-trajectory conditions. For both control conditions, most points fall above the unity line, showing assimilation was stronger for on-trajectory inducers than for stopped inducers for all observers (Figure 1F: $t(12) = 5.8$, $p < 0.001$, $BF_{10} = 333$), and for off-trajectory inducers for all but one (Figure 1G: $t(12) = 4.76$, $p < 0.001$, $BF_{10} = 76$). The assimilation effect clearly depends on target interpolation or extrapolation, rather than to more general spreading of colour signals, or unspecified response biases.

Participants, free to respond at will, tended to respond early, before the inducers reemerged from the occluder (76% of trials). Analysing only those trials shows the effect remained significant (slope –0.34 [–0.73, 0.05], $t(12) = 4.56$, $p < 0.001$, $BF_{10} = 57$): re-emergence of the inducers was thus not essential for assimilation, pointing to motion extrapolation, rather than interpolation.

This study shows the brain maintains a rich spatio-temporal representation of objects passing behind occluders, including accurate information about their colour, which assimilates with that of a probe flashed on the virtual trajectory of occluded motion. Inducers that stopped before slipping behind the occluder, or were probed off-trajectory, had virtually no effect on the perceived target colour, so the assimilation cannot be attributed to memory interference, general contextual effects, decision biases or demand characteristics of the task.

Discontinuous, or ‘stroboscopic’, motion, such as that of motion pictures, is interpolated by the visual system to appear smooth, and the interpolation preserves rich form information[2,3]. But the occlusion durations for smooth stroboscopic motion are far shorter than in this study, tens of milliseconds rather than seconds, and generate motion perception indistinguishable from continuous motion, rather than obviously disappearing behind an occluder. Despite these major differences, the brain may use spatio-temporal mechanisms to interpolate occluded motion that are analogous to those it uses for apparent motion[2], with longer time constants.

Previous work has identified distinct neural responses in early visual cortex during apparent motion[4] and for occluded parts of visual scenes[5,6], a possible neural substrate for these effects. This fits with the view that early visual areas function as a multiscale workspace supporting imagery and visual short-term memory[7], with rich feedback from higher visual areas. Our results point to a precise spatio-temporal representation in early visual cortex that induces colour assimilation effects.

Our visual experience seems continuous despite perceptual gaps caused by blinks, saccades and occlusions, or neural noise, uncertainty and ambiguity. Various mitigating strategies have been proposed to maintain continuity, including ‘continuity fields’[8], involving weighted integration of successive views, also when occluders intervene[9]. Our study is consistent with these ideas, and shows that the representations of occluded objects follow the extrapolated spatio-temporal trajectory, preserving information about object colour. This information is available at relatively low levels of visual processing, allowing it to bias chromatic signals of non-occluded objects. It would be interesting to see if other forms of assimilation — or visual ‘crowding’ — occur with occluded moving flankers.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information including two figures, experimental procedures, data availability, author contributions and one video can be found with this article online at https://doi.org/10.1016/j.cub.2026.01.032.

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