Hierarchical motion perception as causal inference

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Abstract

Since motion can only be defined relative to a reference frame, which reference frame guides perception? A century of psychophysical studies has produced conflicting evidence: retinotopic, egocentric, world-centric, or even object-centric. We introduce a hierarchical Bayesian model mapping retinal velocities to perceived velocities. Our model mirrors the structure in the world, in which visual elements move within causally connected reference frames. Friction renders velocities in these reference frames mostly stationary, formalized by an additional delta component (at zero) in the prior. Inverting this model automatically segments visual inputs into groups, groups into supergroups, etc. and "perceives" motion in the appropriate reference frame. Critical model predictions are supported by two new experiments, and fitting our model to the data allows us to infer the subjective set of reference frames used by individual observers. Our model provides a quantitative normative justification for key Gestalt principles providing inspiration for building better models of visual processing in general.

1 Introduction

If motion can only be defined relative to a reference frame (Hoefer et al., 2023), what is the brain's reference frame for the perception of a moving object? A century of psychophysical studies has provided us with evidence that motion is alternatively perceived in a retinotopic reference frame (Adelson and Bergen, 1985), in allocentric (world) coordinates (Warren and Rushton, 2009), or coordinate frames defined by other objects in a visual scene (Johansson, 1950; Restle, 1979; Gogel and Koslow, 1972; Gershman et al., 2016; Wu and Spering, 2022). Interestingly, perceived motion can rarely be explained by a single reference frame. For instance, in the famous Johansson illusion (Johansson, 1950), while the perceived velocity of the center dot is clearly biased away from the observed retinal velocity, it is not vertical as predicted by a reference frame defined by the flanker dots. Equally, the "flow-parsing" hypothesis (Warren and Rushton, 2009) proposes that the brain subtracts optic flow signals that are compatible with self-motion in order to make us perceive object motion in allocentric coordinates; yet, the empirically observed subtraction is rarely complete (Niehorster and Li, 2017)

Importantly, our perception of motion appears to be closely linked to an observer's perception of the "Gestalt" of a scene, its structure, or configuration (Wertheimer, 1912). Recent work has made some progress in mathematically formalizing this elusive concept of a Gestalt: first in information-theoretic terms (Pomerantz and Kubovy, 1986; Restle, 1979), and more recently in closely-related Bayesian terms (Froyen et al., 2015; Feldman, 2009; Jäkel et al., 2016). A Bayesian formulation, compatible with the widely influential idea that the brain combines incoming sensory information with prior expectations to form subjective beliefs about the outside world (Von Helmholtz, 1867; Knill and Richards, 1996), has the advantage that these priors can be justified by the statistics and structure of the outside world. Yet, existing Bayesian accounts of motion perception are either formulated in a purely retinotopic reference frame (Weiss et al., 2002; Stocker and Simoncelli, 2006) or use priors that are not justified by our knowledge about the world but instead "put in the Gestalt law that we want to get out" (Jäkel et al., 2016). Furthermore, quantitative empirical tests of these models are based on explicit questions like "Do you perceive structure A or B?" (Gershman et al., 2016; Bill et al., 2020, 2022; Yang et al., 2021) which are known to be susceptible to decision biases (Noel et al., 2022).

On a mechanistic level, motion signals are processed locally in early visual areas, and the brain needs to combine information across these local motion detectors to form a coherent percept. A long line of research has modeled how these early areas detect local motion (Hassenstein and Reichardt, 1956; Adelson and Bergen, 1985) and how, through a series of linear-nonlinear stages, this local motion can be combined into a more global motion percept (Adelson and Bergen, 1985; Rust et al., 2006). While integrating these local motion signals allows the brain to solve the 'aperture' problem (Braddick, 1993), it is not always useful for the brain to integrate information. In fact, local motion differences are a powerful segmentation cue, and several studies (Gogel and Koslow, 1972; Braddick, 1993) have shown how our brain contrasts local motions to perceive relative motion. It is however unclear how the brain decides between these two opposing operations, integration and segmentation.

A separate line of research (Körding et al., 2007) in multisensory integration has modeled how the brain solves a similar problem of deciding when to combine information across cues in a Bayesian framework ('causal inference'). Given the general nature of this problem of deciding when to combine information, causal inference has been proposed to be a universal computational motif across the sensory cortex (Shams and Beierholm, 2022). In motion perception, causal inference has been used to successfully explain biases in estimating heading direction from both visual and vestibular cues (Acerbi et al., 2018; Dokka et al., 2019), but not the perception of moving objects.

Here we present a hierarchical causal inference model that overcomes all of the above challenges by performing joint inference over the hierarchical structure of a scene and the motion of individual visual elements within it. Importantly, the motion priors in our model are justified by motion in the real world, in which most objects are not merely slow, but exactly stationary with respect to their canonical reference frame (Knill and Richards, 1996). We also present new data from two psychophysical experiments in humans that probe the hierarchical perception of motion and that provide strong support for the key elements of our model, in particular its hierarchical structure, novel prior, and approximate computations.

2 Results

Motion is perceived in dynamically inferred reference frames that reflect the causal structure of the world

Much of the world consists of approximately rigid objects who in turn are made up of approximately rigid parts. During translation, all points on a rigid object move in the world at the same speed. Consequently, a common velocity for multiple moving elements in a visual scene acts as a strong cue that the elements belong to a single object. Not surprisingly, when we observe a group of dots moving at the same speed (Figure 1A, top), our brain combines them into one object that it perceives as moving (Figure 1A, bottom), rather than perceiving the individual parts as moving independently (Wertheimer, 1912; Jansson and Johansson, 1973). This common velocity cue also allows the brain to segment the scene into multiple moving objects. For example, when we observe the dots moving as shown in Figure 1B, top, we perceive two partially overlapping objects moving at their respective velocities (Figure 1B, bottom).

Importantly, objects do not simply move independently in the world, but are related to each other through hierarchical whole-part relationships. When a part moves differently from the whole, the whole becomes a natural frame of reference in which to represent that part's motion. For example, the body is the natural frame of reference for the motion of an arm because of the causal whole-part relationship between the two: any change in the motion of the body is directly translated into a change in the motion of the arm.

Our key idea linking retinal observations to percepts in Figure 1A-D is that the brain dynamically constructs reference frames within which most of the visual elements it contains are stationary. We formalize this aspect of the physical world by extending the traditional slow-speed prior (Stocker and Simoncelli, 2006) over moving objects to include a mixture component consisting of a delta at 0. This is shown graphically in Figure 1E, where α denotes the prior probability that an object is stationary. This prior acts on the relative velocities of the visual elements represented in this reference frame. This brings us to the central motif in the generative model we propose is used by the brain to perform inference (Figure 1F). The motif specifies how the velocity of an object is the sum of the velocity of the reference frame and the velocity of the object within that reference frame. This sum is probabilistic, allowing for computational imprecision as quantified by σ_{Δ}^2.

Inference within this generative model motif leads to a decomposition of the observed velocities of visual elements into the velocity of a (shared) reference frame and each element's velocity relative to that reference frame. The degeneracy of this decomposition is broken by the mixture prior over the relative velocities, which leads to an automatic "chunking" of moving elements into groups that are inferred to move together. We hypothesize that the perceived velocity of a visual element moving in a reference frame is its relative velocity to the reference frame velocity if the relative velocity is non-zero and the reference frame velocity otherwise. This is compactly illustrated in our model by adding a shaded gray box around the candidate variables for perception in the generative model. Under this illustration, the percept corresponds to the candidate velocity that is non-zero and lowest in the model hierarchy (closest to the observations).

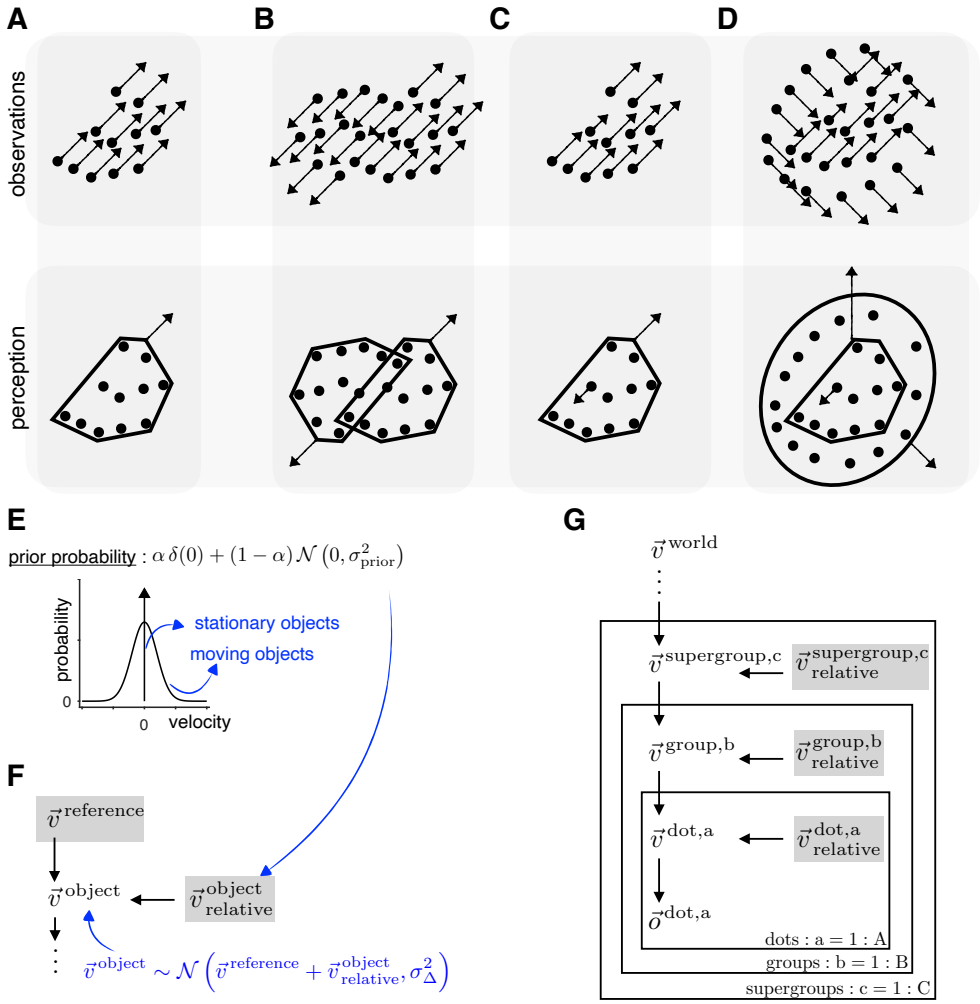

Figure 1: **Causal inference model for hierarchical motion perception.** **(A-D)** Illustration of four different dot patterns that are observed to move as shown in the top row with the arrows indicating retinal velocity vectors. The bottom row shows our predicted motion percept where the brain uses common velocity information to combine dots into objects and group objects into a hierarchical structure. **(E)** Prior that consists of a mixture of a delta distribution at 0 and a Gaussian distribution centered at zero, reflecting the knowledge that elements are either exactly stationary in an appropriate reference frame or are likely to move with a slow speed. **(F)** Generative model motif in which the object's observed retinal velocity is the sum of the reference frame velocity ($\vec{v}^{\,\text{reference}}$) and its velocity with respect to the reference frame ($\vec{v}^{\,\text{object}}_{\text{reference}}$). **(G)** Hierarchical causal inference model obtained by repeatedly applying the motif in F. Inference in this model leads to hierarchical grouping of dots, and representing dot motion in reference frames defined by the groups they belong to. The percept is determined by the non-zero relative variable lowest in the hierarchy.

Recursively applying this motif leads to our proposed hierarchical causal inference model describing velocity percepts in a scene consisting of dots moving according to hierarchical causal relationships. Our model combines dots into groups, groups into supergroups, and so on (Figure 1G). At the bottom of the model are the actually observed velocities in retinal coordinates, $\vec{o}$, which are linked to the latent variables $\vec{v}$ by a Gaussian likelihood whose width represents the observational noise. The top level of the hierarchy is the velocity corresponding to the stationary objects in the world in the egocentric reference frame. For stationary observers this is zero, but for moving observers it is equal to the optic flow velocity caused by self-motion. This allows for a natural extension of this model to explain deviations in perceived velocities due to self-motion (Warren and Rushton, 2009).

Performing Bayesian inference in this generative model requires computing a posterior belief over all possible structures in which the visual elements could be grouped, and over all the velocities in each of the structures. Before empirically testing the quantitative predictions of this model, we next explain the intuitive impact of its key elements using an increasing number of moving dots, building up to explain the classic Johansson illusion.

Illustrating the causal inference model for dot stimuli consisting of 1-3 dots

We illustrate the key features of the model by applying it to very simple stimuli consisting of two or three dots. The model infers full posteriors over all possible structures and the velocities within each structure. For compactness, we focus on the most probable structures and show the most likely inferred velocity using vectors instead of variables in the generative model, as shown in Figure 2A for a simple stimulus in which a single dot is moving. We explicitly show the variables for the rest of the structures in Figure S1.

When observing two dots that move with the same velocity, there are two primary structures that can explain the observations: one in which both dots are moving independently, each represented in the egocentric coordinate system as an individual dot (Figure 2B, left structure), or a structure in which each dot can be inferred to be stationary with respect to a group (an abstract object), consisting of both dots, with the velocity of the group corresponding to the retinal velocity of the dots (Figure 2B, right structure). The delta component of our mixture prior over the relative velocities ensures that the latter hierarchical structure has the highest likelihood given the data since it has the fewest non-zero relative velocities. Furthermore, since the observed velocities for each dot will slightly deviate from each other due to observation noise, the group velocity combines both observations to obtain a more reliable velocity percept of the group (Ernst and Banks, 2002). This combination of dots into a single group occurs for all dots in the scene that are inferred to move with the same velocity.

If a third dot is added to the scene that moves with a different velocity from the other two dots, the two plausible structures to explain the observations are: (a) an object consisting of the two coherently moving dots plus an independently moving third dot (Figure 2C, left) and (b) a single object consisting of all three dots in which the differently moving dot is represented as moving in the object's reference frame (Figure 2C, right). The slow speed component in our mixture prior favors the latter structure if the differently moving dot has a smaller speed in the object's reference frame than in the stationary egocentric reference frame. For instance, in the Johansson illusion (Figure 2C), the third dot has a small relative velocity with respect to the two coherently moving dots, and its perceived velocity is indeed biased towards its velocity in the reference frame provided by the group made up of the two dots (dark green vertical arrow in Figure 2C, right). However, it is important to recognize that even for as little as three moving elements, there are 16 different structures, for instance one in which dots 2 & 3 move relative to dot 1 rather than the other way around, or where all dots move relative to a reference frame defined by all of the dots together, moving at an intermediate velocity. So it may not be surprising that structure (b) alone cannot explain human observers' percepts which sometimes correspond to the retinal velocity suggesting structure (a), sometimes correspond to the relative velocity (structure (b)), and sometimes lie in between (Hochberg and Fallon, 1976; Shum and Wolford, 1983), suggesting that the brain performs inference over multiple, if not all, of these possible structures.

Furthermore, model predictions will depend on how perception is related to the posterior over structures and velocities. Prior work (Gershman et al., 2016) has suggested the mean for the most likely structure, but it could also correspond to the mean across structures as in other work on causal inference (Körding et al., 2007), or posterior sampling (Vul et al., 2014; Wozny et al., 2010).

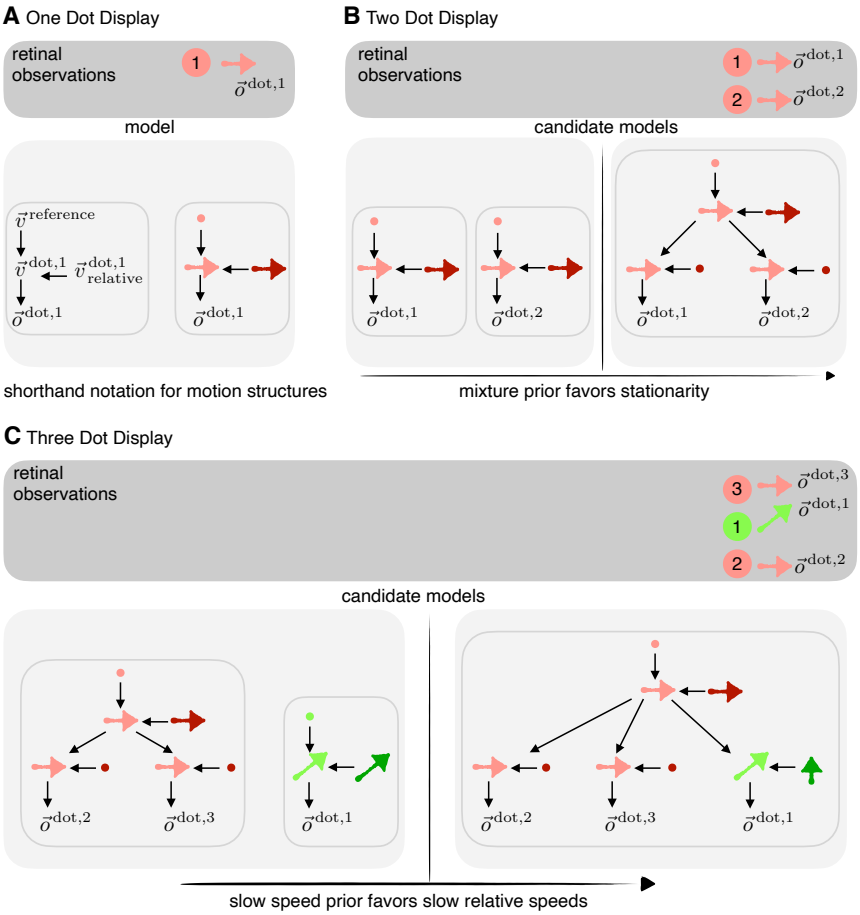

Figure 2: **Model predictions for simple dot stimuli. (A)** The motion of a single dot is inferred in the reference frame of a stationary world. In our shorthand notation, velocity variables have been replaced by their most likely value shown as a motion vector. Darker shades are used to indicate relative velocities and filled circles indicate zero velocity. **(B)** Two moving dots are explainable by two possible structures (left and right). If they move coherently, such that both are stationary with respect to a moving group, the delta component in the prior implies that most posterior mass lies on the combined structure (right). As a result we perceive a moving object consisting of both dots. **(C)** If a third dot is added to the display in (B), the observations are explainable by 8 different structures (Methods, Figure S9), two of which are shown here. On the left, the green dot is perceived as independent of, and unaffected by the motion of the red dots. On the right, the green dot is part of the same structure as the red dots, and perceived in a reference frame defined by a group in which two out of the three dots are stationary (favored by the delta component in the prior). The Gaussian component of the prior favors the right structure over the left one since the velocity of the green dot in the reference frame defined by the red dots is smaller than its velocity with respect to the stationary world. This explains the Johansson illusion Johansson (1950).

New empirical tests of model predictions

In order to quantitatively distinguish between our model and previous proposals, we designed two motion estimation tasks that tested the key elements of our model: (i) the novel mixture prior over relative velocity with a delta at zero, and (ii) the linking hypothesis mapping the posterior distributions over velocities in the model to the distribution over perceived velocities. Importantly, by using a motion estimation task, we test both causal inference over reference frames, and the perception of motion within a reference frame.

Experiment 1: Test using stimuli with two potential levels of hierarchy

In order to test our model, and to constrain its parameters, Experiment 1 was designed to precisely measure human motion perception during the transition from integration to segmentation. Observers used a dial to report their perceived motion direction of a patch of green dots, surrounded by a variable number of patches of red dots (Figure 3A). Surround dots were either stationary, or moving horizontally (direction 0 degrees). The number of surround patches was randomly chosen every trial from $\{1, 2, 3, 5, 10\}$, while the center always consisted of a single patch of dots. Additionally, the retinal center direction (direction on the screen) was randomly chosen on each trial from the set $\{0, \pm 2.5, \pm 5, \pm 10, \pm 20, \pm 45\}^\circ$. The center and surround had a common horizontal velocity (0°), such that the direction of the center's velocity relative to the surround was $\pm 90^\circ$ depending on the sign of the center direction (more details in Methods). As expected, reported directions lie along the identity line when the surround is stationary (Figure 3B).

When the surround is moving, observer responses systematically deviate from the identity line (Figures 3C-G, S4). Specifically, responses are biased towards zero degrees (surround direction) for small center directions, consistent with the observer integrating the center and surround velocities and reporting the cue-combined velocity. The reported velocities are biased towards 90° for larger center directions, consistent with the observer perceiving the relative velocity between the center and surround.

The responses are in excellent agreement with our causal inference model predictions which are overlaid as violin plots. The absolute goodness of fit was measured by variance explained (VE) to be between 92-96% across observers. Also note the clear evidence of causal inference – uncertainty whether to integrate or segment – in the form of bimodal responses (or increased variability) for intermediate center directions around 5° visible in both empirical responses and model fits. These characteristic deviations between retinal motion and perceptual reports depend on the number of surround patches, also in agreement with the model fits (Figure S3 with an average VE of 94%).

We also found clear quantitative empirical signatures of the shift from integration to segmentation using a model-free analysis. To get an interpretable estimate of the effect of the surround on the center, we mapped responses to a modulation index. This index lies between -1 and $+1$, where -1 corresponds to complete integration (perceiving the surround direction), 0 corresponds to the surround having no effect, and $+1$ corresponds to complete segmentation (perceiving the relative velocity between the center and surround; see Methods for details).

The mean modulation index, averaged across observers (Figure 3H) is negative indicating integration, for 2.5° ($p < 0.001$ for the group, $p < 0.05$ individually for 4 out of 5 observers, based on 5000 bootstrapped samples). For larger separations (greater than 10°), the average and individual mean modulation indices are positive indicating segmentation for larger separations ($p < 0.001$). The standard deviation of modulation index, averaged across observers (Figure 3F) is largest for intermediate separations ($p < 0.01$ for the difference in the standard deviations of the modulation index at 5° and at 2.5° and 45°) indicating a higher variability due to uncertainty over causal structures, in agreement with our model predictions.

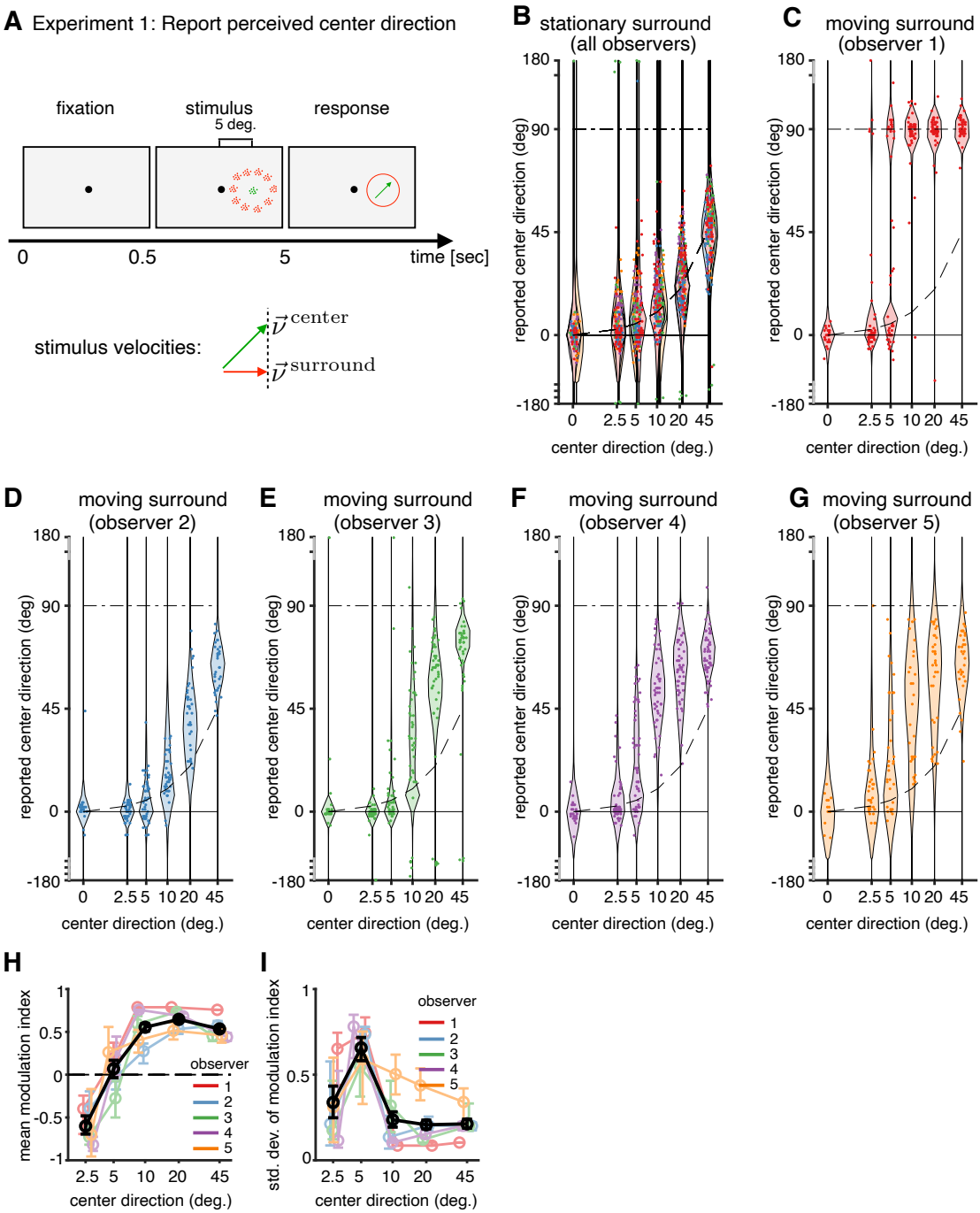
A Experiment 1: Report perceived center direction
fixation
stimulus
5 deg.
response
0
0.5
5
time [sec]
stimulus velocities:
$\vec{v}^{\,\text{center}}$
$\vec{v}^{\,\text{surround}}$
B stationary surround (all observers)
C moving surround (observer 1)
D moving surround (observer 2)
E moving surround (observer 3)
F moving surround (observer 4)
G moving surround (observer 5)
reported center direction (deg)
center direction (deg.)
180
90
45
0
-180
0
2.5
5
10
20
45
H
mean modulation index
1
0.5
0
-0.5
-1
2.5
5
10
20
45
center direction (deg.)
observer
1
2
3
4
5
I
std. dev. of modulation index
1
0.5
0
2.5
5
10
20
45
center direction (deg.)
observer
1
2
3
4
5

Figure 3: **Experiment 1 – design and results. (A)** During fixation, two groups of dots (red and green) appear and move back and forth three times for 4.5 seconds before disappearing. During the last phase of the movement, the fixation dot turned green. The observers adjusted a dial to report their perceived direction of the green dots during the last movement phase. The red (surround) dots were either stationary or moved horizontally (0°), while the green (center) dots varied in direction from trial to trial while keeping the horizontal component of their velocity matched with the surround. **(B)** Responses of all five observers overlaid for the condition where the surround is stationary. Each dot represents a single trial. All responses lie around the identity line (warped due to non-linear spacing of the $x-$axis). Responses were flipped for negative center directions to match the positive directions after verifying that the responses were symmetric. **(C-G)** Responses for each observer when the surround is moving. The horizontal lines at 0° and 90° indicate the predicted reports for complete integration (perceiving the surround) and complete segmentation, i.e., perceiving the relative velocity, respectively. **(B-G)** The overlaid violin plots show the model predictions (not data distributions). One model was fit jointly on all data for each observer. **(H,I)** Mean and standard deviation in modulation index (68% confidence intervals) defined such that -1 corresponds to pure integration, $+1$ to pure segmentation, and 0 to retinal motion. Different colors indicate different observers; black line denotes the average across observers.

Insights from model fitting

We next fit the model to individual responses and obtained posterior distributions over the parameters for each observer (Methods). This allowed us to gain three key insights about the model: (a) whether the mass in the delta component was required to explain the pattern of responses, (b) how observers map the inferred posteriors to responses on each trial, and, (c) how the different causal structures contribute depending on center direction.

Remarkably, for all observers, most of the prior mass was in the delta-component, indicating the strength the brain's expectation that relative motion in the world is exactly zero, rather than merely slow (Figure 4A). We further confirmed the presence of a delta component in the mixture prior by a formal model comparison (Figure 4B, leftmost column) and found strong evidence against a model without as compared to models with mass in the delta component.

Our model comparison (Figure 4B) also revealed that observers' responses are best described as arising from approximate inference (posterior sampling) in the full Bayesian model. We compared this to other previously proposed maps from posteriors to responses: (a) reporting the posterior mean (model averaging) which is the optimal strategy for estimation tasks (Körding and Wolpert, 2004), (b) reporting the conditional mean under the most probable structure (model selection) which maximizes consistency (Stocker and Simoncelli, 2007) and minimizes the description length (Chater, 1996), and (c) reporting the mean by sampling the structure (structure sampling) which is a more precise approximation than posterior sampling (Wozny et al., 2010) (Figure S7). For all observers, the model favored by the evidence had different prior widths and different masses on the delta component for different velocity variables (center, surround, group), performed joint inference over structure and motion, and converted posteriors into responses by sampling.

Our model also allowed us to determine the causal structures underlying each observer's subjective percepts. We found that for all observers, only four out of 16 possible structures were assigned a significant posterior mass (Figure 4C-F for 10 surround patches, and Figures S5, S6 for all other conditions). Under structure 1, the observer integrates center and surround, thus perceiving the cue-combined velocity (Figure 4C). As expected, the posterior probability of this structure was highest when the center and surround moved with the same velocity and decreased with an increase in separation between center and surround velocities (Figure 4G). The bias in the perceived center velocity towards the surround was determined by the weight given to the surround (Figure 4K), which we quantified using the modulation index (as in the previous section). Under structure 2, center motion is perceived in the reference frame defined by the surround – the canonical structure typically assumed for center-surround motion segmentation (Figure 4D,H, L). Unexpectedly, this structure is dominant for only 1 out of 5 observers, plays a transient role for intermediate differences between center and surround motion directions for just 2 observers, and only plays a very minor role for the remaining observers. The same is true for structure 3, under which the surround is perceived in the reference frame of the center, and perception of center motion mostly coincides with retinal motion

(Figure 4E,I,M). Finally, structure 4 implies that both center and surround motion are perceived with respect to a reference that moves at a velocity intermediate to both center and surround (Figure 4F,J,N). This is the structure that carries primary responsibility for intermediate percepts (i.e. the apparently incomplete subtraction of the surround from center velocity) at large differences between center and surround motion directions. Surprisingly, none of the observers places any mass on the possibility that center and surround might belong to different causal structures (the 99th percentile of mass on this structure is below 1% for all observers) – an alternative potential explanation for intermediate percepts. However, one prediction of such a structure would have been to find a substantial fraction of responses along the identity line (given that responses are best explained by posterior matching overall), something that we did not observe (Figure 3C-G). The reason that structure 4 has higher posterior mass than structures 2 and 3 for large separations is the Gaussian slow speed component in the prior: the smaller relative velocities under structure 4 overpower the mass in the delta component of the prior.

As predicted by the model, we also find that both the integration effect (quantified by the model predicted modulation index at 0°) and segmentation effect (quantified by the model predicted modulation index at 45°) become stronger with increase in the number of surround patches (Figure S8B and S8C respectively).

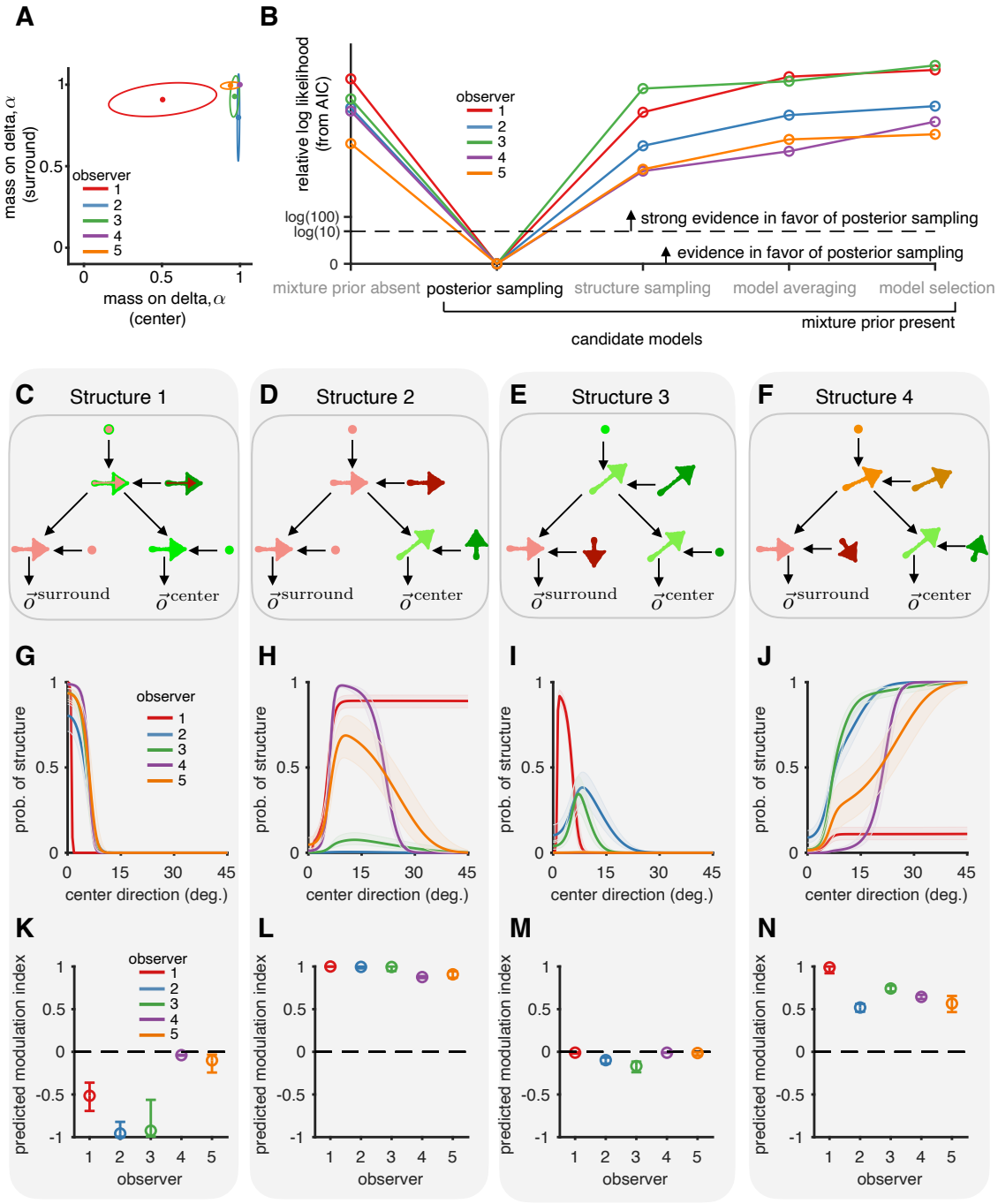
A
mass on delta, α (surround)
mass on delta, α (center)
observer
1
2
3
4
5
B
relative log likelihood (from AIC)
log(100)
log(10)
strong evidence in favor of posterior sampling
evidence in favor of posterior sampling
mixture prior absent
posterior sampling
structure sampling
model averaging
model selection
mixture prior present
candidate models
C Structure 1
D Structure 2
E Structure 3
F Structure 4
o surround
o center
G
H
I
J
prob. of structure
center direction (deg.)
K
L
M
N
predicted modulation index
observer

Figure 4: **Model fitting insights from experiment 1.(A)** Fitted mass on the delta component in the prior for center and surround. Each colored line show the mean and 95% CI for each observer. **(B)** Model comparison. For each model, the difference in AIC score to the posterior sampling model is show. We find strong evidence against all alternative models as compared to the posterior sampling model. **(C-F)** The four causal structures that have a non-zero probability in our model fits. (See main text for description.) **(G-J)** The posterior probability assigned to each structure by each of the observers as a function of center direction. All observers integrate the center and surround for center directions close to zero (C+G) and segments the center and surround otherwise. However, they differ to what degree they rely on each of the three different reference frames implied by D, E, and F. **(K-N)** As in Figure 3E, the modulation index predicted under each structure quantifies the influence of the surround on the perceived center direction. The modulation index for a structure is independent of the probability assigned to that structure. Together, they determine the influence of the surround on the center.

Experiment 2: Test using stimuli with three potential levels of hierarchy

Next, we added a second surround of moving dots to test three key qualitative behavioral predictions of the hierarchical replication of our causal inference motif (possible structures shown in Figure S9). First, motion perception during segmentation is local, i.e. the perceived motion of an element inferred to be moving relative to a group is independent of other motion in the visual scene. Second, if a visual element is integrated with a group, then it inherits the reference frame of that group. Third, the retinal velocity of a group, and not the velocity with which the group is perceived, determines the reference frame velocity for the elements that are part of that group (compare the alternative model in Figure S10 to Figure 1G).

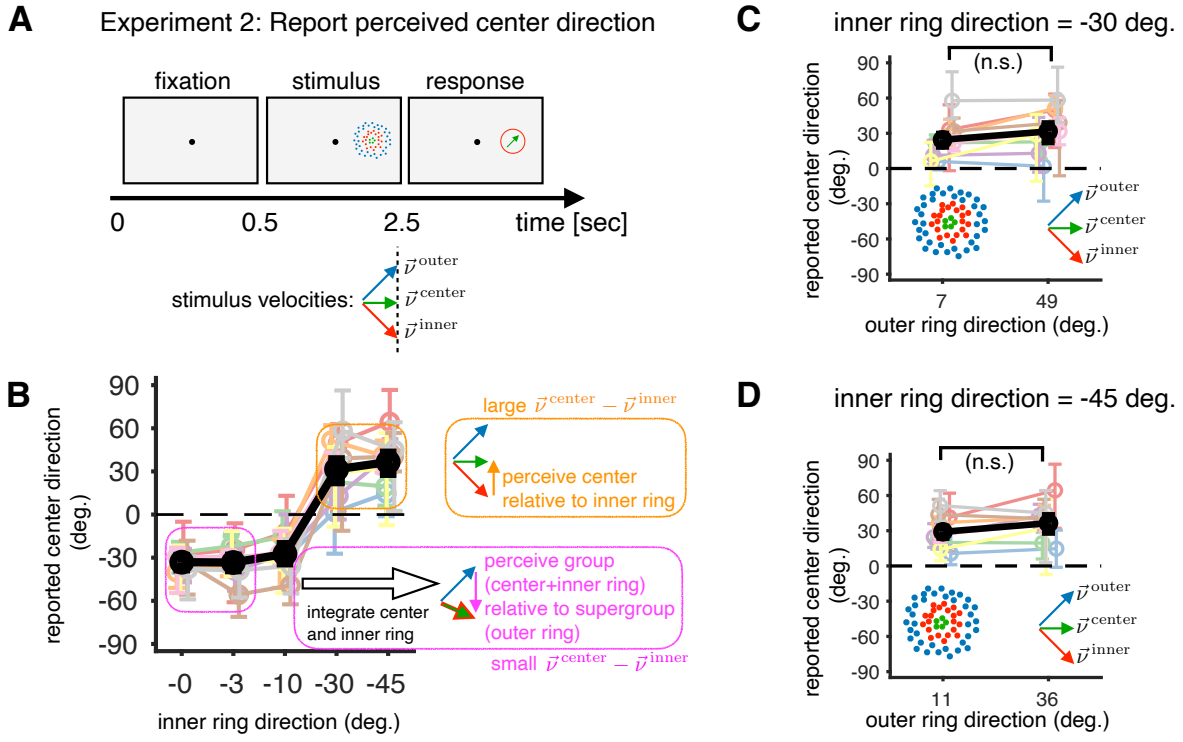

Figure 5: **Design and results of Experiment 2 (three moving groups). (A)** The observer performs an estimation task in which they have to report the direction of green dots (center) using a dial. While center dot directions are randomized from 0 to 360°, results are combined after rotating all velocities such that $\vec{v}^{\text{center}}$ moves horizontally (0°). **(B)** Our model predicts that we will perceive the center dots in the inner ring's reference frame if both move in noticably different directions (segmentation, orange box) and cue combine the center and the inner ring motion if they are sufficiently similar (integration, magenta box). In the latter case, our percept would be the cue-combined center and inner ring's velocity in the outer ring's reference frame. The observer responses support these model predictions. **(C)** The causal inference model predicts that during segmentation, the percept of center motion should only depend on the retinal inner ring motion, not the perceived inner ring motion. The data clearly supports this prediction since the outer ring motion as no influence on the reported center directions (even though it influences the inner ring percepts, see Figure S11). **(D)** Same as (C) but for conditions where the inner ring moves at $-45°$ and the outer ring moves at either 11° or 36°. We consider the two inner velocities that are most different from the center in our experiment to minimize the probability that the observer integrates the center and the inner ring velocities.

As in Experiment 1, observers reported the direction of the center patchmoving in the presence of a surround but in Experiment 2, the surround consisted of inner and outer rings of dots (Figure 5A). The inner and outer ring velocities were on opposite sides of the center patch velocity with the inner ring moving at $\{0°, -3°, -10°, -30°, -45°\}$ counter-clockwise from the center. The outer ring moved at 60° counter-clockwise from the center when the inner ring moved at 0° and the outer ring's velocity was adjusted to maintain a constant relative velocity between outer and inner rings as the direction of inner ring was varied.

The data clearly confirms our model predictions: when the center and inner ring are integrated to form a group, this group is perceived in the reference frame formed with the outer ring (significant biases towards $-90°$, Figure 5B magenta box, $p<0.01$ for all observers). However, when the center is segmented from the inner ring (when its velocity is very different than that of the inner ring), then the center is perceived as moving in the reference frame formed with the inner ring, ignoring the outer ring (reports are biased towards 90°, Figure 5B orange box, significant for 7/9 observers with $p<0.01$).

Our data also supports our model's prediction that the retinal velocity of the inferred group determines the group's reference frame velocity (Figures 5C and 5D respectively). Specifically, as the center is perceived relative to the inner ring when they move differently, the outer ring should have no effect on the percept. Consistent with this, we found no significant difference in reported center directions for different outer ring directions, for inner ring directions of $-30°$ and $-45°$ ($p> 0.05$ evaluated through bootstrapping with 1/9 observers showing significant difference for both inner ring directions). For these inner ring directions, the observers predominantly segment the center and inner rings (Figure 5B, orange box). The individual trial responses are shown in Figure S11.

In addition to the conditions shown in Figure 5B, we also test how: (a) the observers perceive the inner ring in the presence of the center and/or surround, (b) how the center ring percept is biased by just the inner ring moving coherently (similar to Experiment 1) and just the outer ring moving coherently. Responses in these conditions also agree with predictions of the causal inference model (Figure S12C-J).

3 Discussion

We have presented a new model of complex motion perception, and new data to support this model. The key normative ingredients, reflecting the structure of the physical world, are that the motion of visual elements should be represented in reference frames that they are causally connected to, that due to friction forces, the velocity in such a reference frame is mostly zero, and that the world is compositional and hierarchically organized. We designed two experiments in order to test all key elements of our model, to constrain its parameters, and to generate new insights for motion perception in scenes with a richer motion structure than earlier experiments.

Our work advances the large body of work trying to understand sensory processing in terms of natural input statistics (Attneave, 1954; Barlow and others, 1961; Hyvärinen et al., 2009; Laughlin, 1981). Whereas prior work started with the input statistics at the sensory periphery, our model explicitly incorporates causal relationships (moving the whole will move the part) and the importance of friction (the relative velocity is

zero for most objects that are touching each other) for giving rise to these statistics. Strikingly, fitting our model to perceptual reports revealed that most prior mass is in fact at zero for all of our human observers (Figure 4A).

The richness of our our psychophysical data, together with formal model comparison, also allowed us to answer the important question of how the often-complex posterior distributions of a Bayesian observer are related to our deterministic-appearing percept (Block, 2018; Rahnev et al., 2021). In prior work, inference over motion structures and velocities within each structure are treated as separate problems in which either the most likely structure is inferred (Gershman et al., 2016) or the structure is assumed to be known or learned over longer time scales (Bill et al., 2022). Our experiments and analyses provide overwhelming evidence that, at least in the context of motion processing, the brain performs joint inference over both structure and motion, and that perceptual reports are best described by samples from this joint distribution (Figure 4B).

Approximate joint inference in our model can also explain why effect sizes in prior studies usually deviated from previously proposed theories like (Bayesian) Vector Analysis (Johansson, 1950; Shum and Wolford, 1983) or flow-parsing (Warren and Rushton, 2009): a range of different causal explanations are all consistent with the presented impoverished psychophysical stimuli. We confirmed a closely related prediction of our model – the increase in integration and segmentation effect sizes with the number of dots, i.e. the uncertainty in the surround (Zhou et al., 2020) of our experiment 1 (Figure S8).

Fitting our model to individual responses revealed unexpected variability in the causal structures inferred by different observers. We had expected that partial segmentation for large differences in motion direction between center and surround was best explained by observers' lack of confidence that center and surround were indeed part of the same object. However, our quantitative analysis showed this not to be true: partial segmentation was actually explained by observers perceiving both center and surround to be slowly moving with respect to an abstract reference frame moving with an intermediate velocity. A corollary to this result is that the larger the integration bias (i.e. the more the reference frame velocity aligns with the surround), the larger is the segmentation bias, in agreement with earlier work (Wu and Spering, 2022). This result also demonstrated the importance of the 'slow-speed' component of the prior on relative motion – in contrast to the otherwise analogous spike and slab prior (Mitchell and Beauchamp, 1988) common in machine learning.

Earlier work on the influence of context on perception found this influence to be a function of the percept of the context, not the direct sensory input defining the context – both for temporal context effects (Cicchini et al., 2021), and during binocular rivalry (Chopin et al., 2012). Our data from Experiment 2 differs from these findings, confirming that our percepts reflect inference in a model based on the physical laws of motion and suggesting differences between the causal models underlying the ventral and the dorsal processing streams.

While it has long been recognized that both integration and segmentation are key operations underlying motion perception (Braddick, 1993), our model shows that there are in fact two qualitatively different kinds of segmentation: (1) do two visual elements belong to the same causal structure, and, if the answer is yes, (2) is a visual element moving with respect to its reference frame? While our model answers both questions using the framework of 'causal inference' from multisensory integration (Körding et al., 2007), which has been proposed as a 'universal computation' for cortex (Shams and Beierholm, 2022), only the first question corresponds to a question about causality as statistically defined (Pearl, 2009).

Our model also lends itself to making predictions for neurophysiological data. We leave for future work the tantalizing possibility that the two kinds of variables in our model (corresponding to the left and right sides of Figure 1G) are represented by the two major classes of neurons who have been reported (Born and Bradley, 2005) in cortical motion area MT (surround-suppressed and not surround-suppressed).

Bayesian causal inference has recently been proposed as a unifying theory for neuroscience (Shams and Beierholm, 2022). Our model extends the simple 'same' or 'different' scenarios in previous causal inference work to hierarchical whole-part relationships reflecting the compositionality of the world (Lake et al., 2015). The computations at the lowest level of our model in fact resembles a recent probabilistic model of neural responses in primary visual cortex (Coen-Cagli et al., 2015), and the hierarchical architecture of our model directly suggests an equivalent one for the ventral stream, potentially allowing us to understand both dorsal and ventral stream as performing inference in closely related generative models.

Methods

Observers

Five naive observers participated in Experiment 1, and 10 naive observers participated in Experiment 2. Observers provided written informed consent, and were financially compensated for their time. Experiments were approved by the Office for Human Subject Protection (OHSP) at the University of Rochester (IRB number 0003909). 1/10 observers in Experiment 2 was excluded based on their large response variability (standard deviation greater than 30deg) in the control condition and their data was omitted from further analysis.

Experiment 1 details: two moving elements

The stimulus consisted of a 'center patch' of green dots, presented at 5 degree eccentricity. Dots were 0.1 degree in diameter and distributed uniformly within the patch with a density of 6.88 dots/degree^2. The center patch had a radius of 0.68 degrees and was surrounded by a ring of radius 2.72 degrees, consisting of a variable number of patches of red dots (Figure 3A). Each surround patch had a radius of 0.54 degrees and a dot density of 10.91 dots/degree^2. Dot displays were viewed binocularly, and no disparity cues were added, such thatall the dots moved in the plane of the display. The stimuli were presented on a 27-inch monitor with a refresh rate of 60 Hz and a resolution of 1920×1080 at a viewing distance of 105 cm. Eye movements were tracked using an Eyelink 1000 system and trials were discarded in which eyes moved within 1 degree of the center patch.

The stimuli were presented at an eccentricity of 5 degrees in the periphery. The number of dots in a patch was fixed to 10. There was one center patch and the number of surround patches was chosen in every trial from the set [1,2,3,5,10]. The center retinal direction was chosen from the set $[0, \pm 2.5, \pm 5, \pm 10, \pm 20, \pm 45]$ and the surround was either stationary (stationary surround always had 5 patches) or moved at 0 degrees (horizontally rightwards) at a speed of 1 deg/sec.

After a fixation period of 0.5s, the stimulus appeared and moved back and forth for 1.5 cycles. The patch envelopes moved at a constant velocity and reversed their velocity after 1.5 seconds (square wave velocity profile with a time period of 3 seconds). The back-and-forth movement ensured that the envelopes stayed within a fixed area of the screen. In the last half cycle, the fixation dot turned green indicating that the observer had to report the direction during the last half cycle.

After stimulus offset, an arrow appeared at the location of the center patch, and observers used a dial to adjust the arrow direction to match their motion direction percept. The stationary surround condition served as a control. Observers who had a response standard deviation larger than 30 degrees in this condition were removed from subsequent analysis. The fixation period and stimulus had a total duration of 5 seconds following which the observers could make a response at any time to proceed to the next trial. Each observer participated in three sessions to get 22 trials per condition on average for a total of 1446 trials per observer on average.

Experiment 2 details: three moving elements

In experiment 2, the stimulus consisted of a center patch, an inner ring, and an outer ring, all arranged concentrically centered at 5 degrees eccentricity (Figure 5A) separated by 0.5 degrees. On every trial, either the center dots, or the inner ring dots, were colored green, indicating whose direction had to be reported. The other parts of the stimulus contained red and blue dots, respectively, with the color assignment randomly drawn every trial. The number of dots in the center was 10 (density of 3.2 dots/degrees^2 with a center patch radius of 1 degree), the inner ring contained 50 dots (density of 4 dots/degrees^2 with a inner ring width of 1 degree) and the outer ring contained 250 dots(density of 11.4 dots/degrees^2 with a outer ring width of 1 degree). The viewing distance, eye recording details, and the criteria for discarding trials due to fixation breaks and control condition response variability were the same as in experiment 1.

Each trial started with a 0.5 s fixation period during which only the fixation dot was shown on the screen. This was followed by the random-dot stimulus which moved for 2 seconds within an aperture at a constant velocity. Unlike for Experiment 1, the moving dots were presented inside fixed apertures, and the stimulus direction was not reversed. The center moved with a speed of 0.5 degrees/sec and the center direction was

randomized across trials, within a range of 360°, to minimize the effect of reporting biases. The inner ring's retinal direction was chosen from the set $[0, -3, -10, -30, -45]$ relative to the center where negative angles indicate clockwise rotations. The outer ring moved in a counter-clockwise direction chosen such that the same relative velocity was maintained between the outer and inner rings across different inner ring directions. Furthermore, the speeds of inner and outer ring were chosen such that the relative velocity between either ring and center was perpendicular to the center direction.

Different conditions were interleaved across trials in which the inner and outer rings could either move randomly or coherently and the observer had to report the direction of the center or inner ring. As in experiment 1, the observer made their responses by adjusting the direction of the arrow that appeared at the location of the center or inner ring after the stimulus offset with its size matched to the size of the corresponding target. Each observer performed three sessions to get 46 trials per condition on average for a total of 2239 trials per observer on average.

Modulation index to summarize observer responses in Experiment 1

We defined the modulation index, w_{MI}, such that the percept of the center patch ($\vec{v}^{\,\mathrm{center}}_{\mathrm{percept}}$) predicted for a given w_{MI} is given by

$$\vec{v}^{\,\mathrm{center}}_{\mathrm{percept}} = \begin{cases} \vec{o}^{\,\mathrm{center}} - w_{\mathrm{MI}}\vec{o}^{\,\mathrm{surround}} & w_{\mathrm{MI}} \geq 0 \\ (1 + w_{\mathrm{MI}})\vec{o}^{\,\mathrm{center}} - w_{\mathrm{MI}}\vec{o}^{\,\mathrm{surround}} & w_{\mathrm{MI}} \leq 0 \end{cases} \tag{1}$$

where $\vec{o}^{\,\mathrm{center}}$ and $\vec{o}^{\,\mathrm{surround}}$ are the observed center and surround velocities from the brain's perspective for a given trial. This definition incorporates partial subtraction of the surround (case $w_{\mathrm{MI}} \geq 0$) for relative velocities when the effect on perception is repulsive (Mori, 1979) and cue combination (Ernst and Banks, 2002) when the effect is attractive (case $w_{\mathrm{MI}} \leq 0$). Under the simplifying assumption that $\vec{o}^{\,\mathrm{center}}$ and $\vec{o}^{\,\mathrm{surround}}$ correspond to the experimenter-controlled velocities on the screen (ignoring observation noise), and that the perceptual reports exactly reflect the perceived variable $\vec{v}^{\,\mathrm{center}}_{\mathrm{percept}}$ (ignoring motor noise), one could estimate a per-trial modulation index to obtain a distribution over w_{MI} for each separation of center and surround in order to estimate means and standard deviations which unfortunately would be biased. In order to obtain the unbiased estimates reported in Figures 3H and I, we therefore modeled observation noise, motor noise, and motor bias explicitly which allowed us to infer the distribution over w_{MI} from the distribution over perceptual reports (see supplementary section S1 for details).

Causal inference model for hierarchical motion perception

Generative model in a scene with two moving elements

The observed retinal velocities, $\vec{o}^{\,\mathrm{center}}$ and $\vec{o}^{\,\mathrm{surround}}$, were modeled as the true retinal velocities, $\vec{v}^{\,\mathrm{center}}$ and $\vec{v}^{\,\mathrm{surround}}$ corrupted by additive Gaussian noise with variance ${\sigma^2}_{\mathrm{center}}$ and ${\sigma^2}_{\mathrm{surround}}$, respectively ($\mathbb{I}$ refers to a 2×2 identity matrix) :

$$\vec{o}^{\,\mathrm{center}} \sim \mathcal{N}(\vec{v}^{\,\mathrm{center}}, \sigma^2_{\mathrm{center}}\,\mathbb{I}) \quad \text{and} \quad \vec{o}^{\,\mathrm{surround}} \sim \mathcal{N}(\vec{v}^{\,\mathrm{surround}}, \sigma^2_{\mathrm{surround}}\,\mathbb{I}). \tag{2}$$

The velocities were parameterized as two dimensional vectors reflecting the x and y components. In order to model the inference over the different causal structures (here, whether center and surround are part of the same moving group), we follow (Körding et al., 2007) in introducing a binary (logical) variable $S^{\mathrm{center,surround}} \in \{0, 1\}$ (corresponding to the left and right side of Figures 2B and S2B). This allows us to write the conditional probabilities compactly as:

$$\vec{v}^{\,\mathrm{center}} \sim \mathcal{N}(S^{\mathrm{center,surround}}\vec{v}^{\,\mathrm{group}} + \vec{v}^{\,\mathrm{center}}_{\mathrm{relative}} + (1 - S^{\mathrm{center,surround}})\vec{v}^{\,\mathrm{world}}, \sigma^2_{\Delta}\,\mathbb{I}) \quad \text{and} \tag{3}$$

$$\vec{v}^{\,\mathrm{surround}} \sim \mathcal{N}(S^{\mathrm{center,surround}}\vec{v}^{\,\mathrm{group}} + \vec{v}^{\,\mathrm{surround}}_{\mathrm{relative}} + (1 - S^{\mathrm{center,surround}})\vec{v}^{\,\mathrm{world}}, \sigma^2_{\Delta}\,\mathbb{I}). \tag{4}$$

where σ^2_{Δ} models the uncertainty in the velocity composition, e.g. due to computational noise. The prior over $S^{\mathrm{center,surround}}$ is given by $\beta^{\mathrm{center,surround}}$ which represents the prior probability that center and surround belong to a common structure (based on prior experience, or other non-motion cues). In a scene with only

two moving elements, the group velocity is inferred in the stationary world reference frame with $\vec{v}^{\,\text{world}} = 0$ (Figure 1G):

$$\vec{v}^{\,\text{group}} \sim \mathcal{N}(\vec{v}^{\,\text{group}}_{\text{relative}} + \vec{v}^{\,\text{world}}, \sigma^2_{\Delta}\,\mathbb{I}). \tag{5}$$

The prior over each of the relative velocities is a mixture prior of a delta function at zero and a normal distribution centered at zero

$$\vec{v}^{\,\text{center/ surround/ group}}_{\text{relative}} \sim \alpha\,\delta(0) + (1-\alpha)\mathcal{N}(0, \sigma^2_{\text{prior}}\,\mathbb{I}) \tag{6}$$

where α represents the expectation that the (relative) motion is exactly zero (Figure 1E,F).

Mapping inferred latent variables to percepts

Our model predicts that if the center is inferred to be part of the same group a the surround, then the perceived center motion corresponds to the center's relative velocity if it is inferred to be nonzero, and to the group velocity if the center's relative velocity is inferred to be zero. If the center is not inferred to be part of the same group as the surround, then its motion relative to stationary world is perceived. By defining $C^{(\cdots)} \in \{0,1\}$ to denote whether the velocity $\vec{v}^{\,(\cdots)}_{\text{relative}}$ is zero ($C^{(\cdots)} = 0$) or not ($C^{(\cdots)} = 1$), we can compactly write the percept as:

$$\vec{v}^{\,\text{center}}_{\text{percept}} = C^{\text{center}}\vec{v}^{\,\text{center}}_{\text{relative}} + (1 - C^{\text{center}})S^{\text{center,surround}}C^{\text{group}}\vec{v}^{\,\text{group}}_{\text{relative}}. \tag{7}$$

Therefore, the distribution over the observer's percept is a mixture distribution with the mixture weights corresponding to the posterior probability of the different causal structures (characterized by possible S) and the different nested structures within each causal structure (characterized by possible C):

$$\begin{aligned} p(\vec{v}^{\,\text{center}}_{\text{percept}}|\underline{\vec{o}}) = & \sum_{c_1=\{0,1\}}\sum_{c_2=\{0,1\}}\sum_{c_3=\{0,1\}}\sum_{c_4=\{0,1\}} \\ & p(C^{\text{center}} = c_1, C^{\text{surround}} = c_2, C^{\text{group}} = c_3, S^{\text{center,surround}} = c_4|\underline{\vec{o}}) \\ & p(\vec{v}^{\,\text{center}}_{\text{percept}}|\underline{\vec{o}}, C^{\text{center}} = c_1, C^{\text{surround}} = c_2, C^{\text{group}} = c_3, S^{\text{center,surround}} = c_4). \end{aligned} \tag{8}$$

where for compactness we define $\underline{\vec{o}} \equiv (\vec{o}^{\,\text{center}}, \vec{o}^{\,\text{surround}})$. For any number of moving elements, this posterior has the general form:

$$p(\vec{v}^{\,\text{center}}_{\text{percept}}|\underline{\vec{o}}) = \sum_{i}^{N} w_i(\underline{\vec{o}}_j)\mathcal{N}(\vec{v}^{\,\text{center}}_{\text{percept}}; \vec{\mu}_i(\underline{\vec{o}}_j), \sigma_i^2\,\mathbb{I}) \tag{9}$$

where w_i, μ_i, and σ_i^2 correspond to the probability, mean and variance associated with each causal structure, respectively. For n moving elements, the total number of mixture components in the posterior is $N = \#S(n)\,2^{\#C(n)}$ where $\#S(n)$ is the number of possible causal structures and $\#C(n)$ is the maximum possible number of relative velocities (each of which could be zero or not thereby resulting in $2^{\#C(n)}$ nested structures). $\#S(n)$ satisfies the recurrence relation given by $\#S(n) = 2 + \sum_{k=2}^{N-1}\binom{n}{k}\#S(n-k+1)$ as in addition to all elements being independent or part of the same group, grouping k elements results in $n-k+1$ moving groups. $\#C(n) = \frac{n(n+1)}{2}$ as at each hierarchical level i, we can have $n-i$ moving elements where $i \in \{0, N-1\}$. The expressions for the terms in Eq. 9 are derived in supplementary section S2.

The distribution over perceived velocity can be mapped onto the distribution over the perceived center direction, $\theta^{\text{center}}_{\text{percept}}$, by mapping each velocity to its corresponding direction:

$$p(\theta^{\text{center}}_{\text{percept}}|\underline{\vec{o}}) = \int_{\vec{v}^{\,\text{center}}_{\text{percept}}} p(\theta|\vec{v}^{\,\text{center}}_{\text{percept}})p(\vec{v}^{\,\text{center}}_{\text{percept}}|\underline{\vec{o}}). \tag{10}$$

Inserting Eq. (9) into (10), we can approximate the integral to get:

$$p(\theta^{\text{center}}_{\text{percept}}|\underline{\vec{o}}_j) = \sum_{i=1}^{N} w_i(\underline{\vec{o}})\mathcal{N}_{\text{circular}}\{\theta; \hat{\theta}_i(\underline{\vec{o}}), \kappa_i\}. \tag{11}$$

$\mathcal{N}_{\text{circular}}$ represents the von Mises distribution pdf with mean parameter $\hat{\theta}_i(\underline{\vec{o}}) = \arctan(\vec{\mu}_{i,y}, \vec{\mu}_{i,x})$ and concentration parameter $\kappa_i = T_2(\sigma_i^2/||\vec{\mu}_i||_2^2)$ which can be computed numerically. We allow for lapses in responses by adding another component to the distribution over the center direction that is a von Mises distribution characterized by μ^{lapse} and κ^{lapse}.

$$p(\theta_{\text{percept}}^{\text{center}}|\underline{\vec{o}}) = \lambda\mathcal{N}_{\text{circular}}(\theta; \mu^{\text{lapse}}, \kappa^{\text{lapse}}) + (1-\lambda)\sum_{i=1}^{N} w_i(\underline{\vec{o}})\mathcal{N}_{\text{circular}}\{\theta; \hat{\theta}_i(\underline{\vec{o}}), \kappa_i\}. \tag{12}$$

Perceptual estimation

We consider the following four, previously proposed (Körding et al., 2007; Wozny et al., 2010), ways in which the brain may convert the posterior $p(\theta_{\text{percept}}^{\text{center}}|\underline{\vec{o}})$ into a perceptual point estimate, $\theta_{\text{estimate}}^{\text{center}}$:

Model averaging: $\theta_{\text{estimate}}^{\text{center}}$ is the mean of the joint posterior over all structures: $\theta_{\text{estimate}}^{\text{center}} = \sum_{i=0}^{N} w_i'\mu_i'(\underline{\vec{o}})$.

Model selection: $\theta_{\text{estimate}}^{\text{center}}$ is the posterior mean over direction for the most likely structure: $\theta_{\text{estimate}}^{\text{center}} = \mu_{i*}'(\underline{\vec{o}})$ where $i^* = \arg\max w_i'$.

Structure sampling: $\theta_{\text{estimate}}^{\text{center}}$ is the posterior mean over direction for a single structure sampled from the posterior over structures: $\theta_{\text{estimate}}^{\text{center}} = \mu_i'(\underline{\vec{o}})$ where probability of $\mu_i'(\underline{\vec{o}}) \propto w_i'(\underline{\vec{o}})$.

Posterior Sampling: $\theta_{\text{estimate}}^{\text{center}}$ is a direction sampled from the joint posterior over all structures and directions: $\theta_{\text{estimate}}^{\text{center}} \sim p(\theta_{\text{percept}}^{\text{center}}|\underline{\vec{o}})$.

Predicted distribution over observer responses

The distribution over observer reports, R, for a set of experimenter-defined directions $\underline{\vec{\nu}} \equiv (\vec{\nu}_{\text{retina}}^{\text{center}}, \vec{\nu}_{\text{retina}}^{\text{surround}})$ can be obtained by marginalizing out all possible sensory observations (Körding et al., 2007; Acerbi et al., 2014) :

$$p(R|\underline{\vec{\nu}}) = \int_{\underline{\vec{o}}} p(R|\underline{\vec{o}})p(\underline{\vec{o}}|\underline{\vec{\nu}}). \tag{13}$$

We model the distribution over observer reports, R, as a von Mises distribution centered on $\theta_{\text{estimate}}^{\text{center}}$ allowing for a reporting bias b and a motor noise κ_m:

$$p(R|\underline{\nu}) = \int_{\underline{\vec{o}}} \mathcal{N}_{\text{circular}}(R; \theta_{\text{estimate}}^{\text{center}} + b, \kappa_m)p(\underline{\vec{o}}|\underline{\vec{\nu}}). \tag{14}$$

Since this integral is intractable to evaluate analytically, we approximate this using Gaussian quadratures evaluated at points $\vec{o_j}$ with weights w_j^{quad}:

$$p(R|\underline{\nu}) = \sum_j w_j^{\text{quad}}\mathcal{N}_{\text{circular}}(R; \theta_{\text{estimate}}^{\text{center}} + b, \kappa_m). \tag{15}$$

The distribution over observer responses for different perceptual estimates described in the previous section are give in supplementary section S3.

Model fitting details

We obtained the maximum a posteriori (MAP; for initializing the sampler) and maximum likelihood estimate (MLE; to compute AIC) for the model parameters under weakly informative priors (details in Table S1) using a quasi-newton Broyden-Fletcher-Goldfarb-Shanno (BFGS) unconstrained optimization procedure (fminunc in MATLAB). We obtained full posteriors over all model parameters using generalized elliptical slice sampling (Nishihara et al., 2014) which allowed us to get uncertainty estimates for all parameter estimates. We used

144 chains with 25000 samples per chain to estimate the posterior distribution over the parameters (average $\hat{R} \leq 1.1$).

To evaluate the absolute goodness of fit of the model, for each combination of center and surround velocities, we compared the empirical CDF from the reported directions with the corresponding model prediction. We quantified the overall match as variance explained across all conditions.

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Competing Interests

Authors declare that they have no competing interests.

Code and Data availability

Code and data is available at https://osf.io/f9dsg/.

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