Frame Effects across Space and Time

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# Abstract

In the frame illusion, the perceived location of two probes flashed at the same location can be offset from each other by as much as a surrounding frame moves. This frame illusion suggests that we perceive object position relative to the surrounding frame and if that frame is moving, an object is seen in its position relative to a virtually stabilized location of the frame (Özkan et al., 2021). Here we examine first how far the influence of the frame extends over space and time. Here we explore the limits of the frame illusion to better understand how we perceive the location of objects relative to moving frames of reference.

# Introduction

Correctly perceiving the location of objects is important when interacting with them, but this can also be hard when there are other moving objects nearby. When two probes are flashed at the same location when a surrounding frame with periodic movement is at the extremes of its path, the probes can appear offset from each other by as much as the frame moves (PNAS). That is, the location of the probes seems to be perceived relative to the moving frame, rather than in absolute coordinates (Fig. 1). Previously, we explored some limits of the illusion (JoV) and suggested a tentative explanation for the illusion. We suggested that the illusion relies on the probes belonging to or grouping with the frame and being referenced to a “virtual” frame, stabilized at the midpoint of its path. The probes are then seen as located in this virtual frame at the locations they have within the frame when they flash.

Diagram

Description automatically generated

Figure 1. The Frame Effect. Flashed probes are seen at their locations relative to the frame, as if it was almost stationary, shifted far from their physical locations (Movie 1).

Here we test the spatial and temporal extent over which the frame has an effect on the probes.

**Space:** Is the frame’s effect limited to probes appearing inside the frame? We test probe locations within and outside (vertically and horizontally) the horizontally moving frame. Distance between the frame and the probes is also determined by the frame size so that is varied as well. We also test whether the probes have to be at the same plane of depth as the frame

**Time:** Does the frame effect extend in time to probes flashed before or after the presence of the moving frame? We move a frame 1, 2 or 3 times and present probes so they both appear during the last displacement of the frame, or so that only one of the probes appears while the frame is present, or so that no frame is present when either probe is flashed (either before or after the frame’s presentation).

To test the effect of the relative timing of the probes within each motion cycle, we use an apparent motion version with the frame presented only at its two end points. The probes are then flashed at various phases within the motion cycle.

We also test whether the frame effect is affected when the frame’s motion is generated by hand motions of the participant. We compare the strength of the frame illusion with self-moved frames (using a metronome-like guide for timing) to that seen with standard frames.

**Frame motion:** If the frame consists of a set of points: do we use the background motion as reference frame or is it the whole object? We test a larger set of dots covering the screen from left to right, as well as a square set of dots. Within these square sets of dots, we have the dots move with the frame, have them static such that the edges of the frame are perceived by dots disappearing on one end and disappearing on the other, and we can even have them move in the opposite direction as the frame. For control, participants indicate the amount of motion they perceive.

**Practice effect:** It is beneficial to perceive the true position of objects, rather than their illusory position. Does this illusion reduce over time? All 9 tasks were run on the same participants in one session during approximately 2 hours of testing. We analyzed these results across tasks to see if the strength of the illusion changes with increasing exposure.

# Methods

## Participants

X unpaid volunteers were recruited from the lab as participants, including the first author (age: X-X, females: X). All had normal or corrected-to-normal vision and provided prior, write informed consent. All procedures were approved by the York Human Participants Research subcommittee.

## Setup

Stimuli were presented on a Dell XXXX monitor (1680x1050 pixels; 60Hz; X/Y cm) which was kept at 60 cm distance from participants eyes using a chin rest. The screen's gamma function was linearized and the background set at 50% luminance gray. In most tasks, participants indicated their percept using a mouse (the horizontal coordinate), and finalized their response by pressing the space bar on a keyboard. In one task (self-moved frames) the participants moved the frame by themselves using a stylus on a drawing tablet (Intuos Pro Large), where a card-board stencil with a 12 cm horizontal gap kept the stylus within range, while allowing easy control of the frame (see methods for more details). During another task (anaglyph/depth), and its' calibration and control task, cardboard red/cyan filter glasses were worn by the participants (over or under their regular glasses, however it was most comfortable to them).

## Tasks

In all tasks, the standard frame is a 7x7 dva square on the outside, which has a white (100% of the monitor's luminance) edge of 0.5 dva width. The standard frame motion spans 4 dva. The two probes are blue (top) and red (bottom) circles with a diameter of 1 dva positioned 1 dva above and below the middle of the frame path. The frame stopped moving for Y ms at the extremes of its' horizontal path, in the middle of this pause, the probes were flashed for X ms (cf. PNAS paper).

For all trials, participants were given two continuously visible reference dots whose position could be controlled with a mouse. Participants were instructed to position the reference dots such that their slant matched that of their percept. The frame motion is randomly flipped left-right on each trial, such that the illusions direction is not predictable.

All blocks of each task had the same trials, but in a shuffled order. The order of tasks was shuffled as well. For each participant the seed of the random number generator was set using the participant ID.

Details of all tasks are described below, first the tasks testing generalization of frame effects across space in the fronto-parallel plane and in depth, and then across time. These are followed by the tests of the frame effect with self-motion of the frame and finally, the tasks testing the nature of the frame’s motion. The data analysis for each task will be explained right before each set of results.

### Space: Frame offset and size and depth

In this task, we test two spatial aspects of the illusion. First we offset the frame from the probes by 0, 3, 6, 9 and 12 dva, both horizontally or along the direction of motion of the frame (to the right) and vertically or orthogonal to the direction of motion of the frame (upward). Second, in each position, the frame is at the standard size of 7x7 dva square on the outside, or it is a 4x4 or a 10x10 dva square, in each case with a 0.5 dva wide outline going inward. At the smallest size, the probes are displayed on the edge of the frame, and this also happens at some of the offsets. The period of motion is ¼ s in all stimuli in this task.

There are stimuli for testing the effect of time-on-task on the strength of the illusion in this task, where there is no vertical of horizontal offset and the

We test …

All offsets are achieved by offsetting the cyan and red parts of each object by 1 dva.

First, we let participants calibrate the red and cyan (green & blue) contributions to minimize double perception of stimuli. Then they indicated which of two dots presented centrally was in front (one at the top, or one at the bottom). These dots had 1 dva diameter, and their centers were separated 2 dva, exactly like the probes. Since we also used the same 3 depths as used in the frame illusion (see below) there are 6 possible stimuli

In the tests of frame illusion, there are 4 stimuli: 1) both dots and the frame are in the standard plane of depth, 2) the frame is behind the regular plane of depth and the dots in front of it, 3) the frame is in front of the regular plane of depth and the dots behind it, 4) the frame is at the regular plane of depth and the top probe is in front while the bottom probe is behind the frame.

### Time

*Continuous frame motion:* Here we test if whether the frame effect extends in time before and after the presence of the moving frame. The frame may cover one, two or three cycles of motion. The flashed probes are also either both shown in the first (or last) movement of the frame, with one probe present simultaneously with the frame or neither flashed probe. In each trial the sequence of stimuli is presented repeatedly until participants finalize their response. In this task, the frame motion is 4 dva per ¼ s.

Since flashing probes during the first and last frame movement is the same for a single frame movement, there are 17 conditions. Each of these is shown twice during each block, and 4 trials are added to each block to test the effects of time-on-task on the strength of the illusion, using flashed probes presented during a single frame movement. This means each of 4 blocks consists of 38 trials and that each condition for this task is repeated 8 times.

*Apparent frame motion*: Here we test the effect of the synchrony of the probes and the point of reversal of the frame’s motion. For this, we use an apparent motion frame where the frame is only present on the screen at the path end points. In previous studies (Özkan et al., 2021; Cavanagh et al., 2022), the probes are flashed when the frame reverses direction at the extremes of its movement. The probe is flashed with a range of lags after (or before) the frame’s presentation.

We use a motion duration of ⅓ s

### Self-moved frame

To test if efference-based predictions of motion affect the illusion (either strengthening or weakening it) or not, we asked participants to move a frame back and forth in synchrony with a metronome, by moving a stylus left and right within a slot in a stencil on a drawing tablet. Participants simultaneously used their left hand on a keyboard to report their percept by moving reference dots left and right with the left and right arrow keys and finalized it by pressing the up arrow key. The (standard) frame was to be moved 4 dva per ½ s in 3 conditions: 1) the position of the stylus mapped onto the position of the frame such that moving the stylus right moved the frame right as well, 2) the position of the frame mirrored that of the stylus such that moving the stylus right moved the frame to the left, and 3) the experiment moved the frame perfectly according to the metronome.

Each of these conditions was repeated 5 times, such that each of the 3 blocks consisted of 15 trials. There were no stimuli in this task to test the effect of time-on-task.

### Limited dot-lifetime frames

In this task, frames and a larger background area each consisting of limited-lifetime dots were compared with a regular outline frame to test what kind of frame motion is necessary for the illusion to occur. The regular frame was a 7 dva square (outside), with a 0.5 dva white outline. Frames consisting of the dots could have the outer dots edge span up to 3.5 dva away from the centre of the frame. The background strip of dots had no vertical edges but spanned the width of the monitor. Dots are 0.4 dva squares, had a lifetime of 1 s and were 30%, 40%, 60% and 70% gray (in the monitor's luminance range) and they moved with the "frame" (which could be seen as acting as a virtual aperture).

The default frame movement period was ⅓ s in this task (plus the stationary part), but for both the classic frame and dot background stimulus, frame movement periods of 1 s, ½ s, ¼ s and ⅕ s were also used. Thus, there are 5 versions of the classic frame and the dot background stimulus.

Frames consisting of limited lifetime dots could have the dots move with the frame (they only appeared and disappeared based on their lifetime), they could have stationary dots (that also appeared and disappeared based on the virtual frame 'aperture' position) or they could in the opposite direction of the frame or in the same direction as the frame but twice as much (or twice as fast). These 4 variations were only shown with the (virtual aperture) frame moving for ⅓ s and 4 dva.

The task had 3 blocks where each of the 14 stimuli were shown 4 times for 42 trials, and half of the classic frames were presented with a fixation dot at the centre of the screen. In this case participants were instructed not to look directly at the frame and probes but to assess the illusion only while looking at the fixation dot. They were allowed to look at the reference dots while adjusting them to match their percept.

For the test of illusion strength across time-on-task, the classic frame (and dot background) stimulus were also presented with movement amplitudes of 0.8, 1.6, 2.4 and 3.2 dva twice each block, for an additional 16 trials, such that each of the 3 blocks had 58 trials.

### Limited dot-lifetime motion perception

Since the amount of perceived motion could affect the strength of the illusion in the previous task, we wanted to test how much motion was perceived. To do so we presented the classic frame and dot stimuli without flashed probes. Instead of the reference probes, participants were given a horizontal bar and they could adjust the length such that it matched how much they thought the frame or set of dots moved in each direction.

The classic frame and the dot-background stimuli (same properties) are tested at different movement durations / speeds (4 dva per 1, ½, ⅓, ¼ or ⅕ s) which are each presented 3 times in a block. They are also tested at different movement amplitudes (4, 3.2, 2.4, 1.6, and 0.8 dva per ⅓ s), but since the larger amplitudes are already in the previous set, only the 4 shorter amplitudes are tested, each once per block.

The 4 types of limited lifetime dots with a virtual aperture frame are each shown 3 times per block at 4 dva per ⅓ s. That is, each of the 3 blocks had 52 trials in total. There were no stimuli in this task to test the effect of time-on-task.

### Time-on-task

The brain learns to see through some illusions over time, so here we do a first test to see if the frame illusion decreases with time-on-task in this experiment. The time it took participants to complete all the tasks (including breaks) ranged from ~80 minutes to almost 3 hours, so we assess this in 4 epochs of 30 minutes. We use a set of standard trials inserted in some of the tasks: 1) Limited dot-lifetime, 2) Offset and size, 3) Pre- and postdiction and 4) Apparent motion.

The duration (speed) of the frame varied slightly between these tasks. We have shown this does not affect the illusion (CITATION… or maybe analyze this in the limited dot-lifetime data here). The illusion is a function of the amplitude of the frame's motion however, and we used 5 different motion amplitudes here (4, 3.2, 2.4, 1.6 and 0.8 dva). In one task, the first 7 participants used a motion amplitude of 1.8 dva instead of 1.6 dva, and this data is not used (for now). We can get an average + 95% confidence interval of illusion strength across these 5 different motion amplitudes as a percentage of the motion, and test if this measure of illusion strength changes from one 30 minute epoch to the next.

There is a differently randomized order of tasks for every participant, so that we get counterbalancing of any task effects as best as we can, but there will still be 30 epochs with no data for some participants. To be able to analyze the data nevertheless, we fit a linear mixed effects model with illusion strength as the predicted variable, 30 minute epoch as a fixed effect and participant as a random effect. For interpretability we then convert this to ANOVA-like output using the Satterthwaite method (CITE).

# Results

## Frame effects in space

### Frame offset and size

We find that the frame effect (the illusory offset between the two flashed probes) decreases following a sigmoid function when the distance between the frame and probes increases. This suggests a Bayesian-like integration process assigning "belongingness" between the frame and probes based on their spatial proximity. It also means that we can fit an inverted cumulative normal distribution to assess the distance where the frame effect has decreased to 50% of its strength as a characteristic of this process for statistical analysis.

We also see that the direction of offset affects where the strength of the illusion drops below 50%, and this makes sense if we consider that horizontal offsets are partially undone by the movement of the frame which (for some part of the stimulus) will bring the frame closer to the probes again and this does not happen in vertical offsets.

Finally, we see that this function is modulated by the size of the frame, which makes also sense since a larger frame offset by the same amount from the probes will have the outer edge of the frame closer to the probes than a smaller frame.

In the previous figures, the distance between probes and frame was expressed as the distance between the centre of the frame and a point right between the two probes. Given the data, the modulation of the 50% could disappear if we express the offsets as the shortest distance between either probe and any edge of the frame during a full cycle of the stimulus.

### Plane of depth

If the distance between the frame and probes affects the strength of the illusion, we wonder if this extends in depth as well. However, within the depth differences tested, we see no difference in the strength of the illusion.

Taken together the results on spatial "belongingness" seem to suggest that this could be a function of retinal proximity, rather than perceived proximity.

## Frame effects in time

### Pre- and postdiction

There is a full illusion when both probes are flashed during any frame movement, there is a weak illusion if one of the probes is flashed while the frame is present as well, and there is no illusion if the probes are flashed in the absence of the frame. This is not modulated by how many movements the frame made (1, 2 or 3), or by whether the probes are flashed after the frame moves (prediction) or before the frame moves (postdiction).

This is reminiscent of (Mohammad Shams '22 VSS poster; exp X) although here we find no effect of …

### Apparent motion frame with lagged probes

The illusion strength is decreased in the apparent motion frame, and while it was possible that increasing probe lag could decrease illusion strength (relatively) faster in the apparent motion frame because probes and frame are not presented simultaneously, it seems that the relative drop in illusion strength is comparable for lagged probes in the classic frame and the apparent motion frame. This suggests that in the apparent motion frame, the frame position is interpolated between the two extremes.

Maybe the illusion would be stronger if the frame moved normally before the apparent motion jump? (I.e. we have a stimulus with a normally moving frame but no probes, and the frame glitches away between extremes exactly on the passes where we flash the probes? No lags!) If this does increase illusion strength this would mean that the normal motion strengthens the interpolation in the apparent motion part, if not this would mean that the illusion really happens in the moment only.

Perhaps motion aftereffects can give rise to a frame effect, but these stimuli should not elicit motion aftereffects.

### Self-moved frame

In the three types of stimuli here: congruent self-moved frame, incongruent self-moved frame and classic control frame, there was no difference in strength of illusion.

Taken together these tests of the frame's motion indicate that it is the visual motion of a frame with visible edges that allow the frame illusion to occur.

## Frame motion

### Limited dot-lifetime frames

Perceived motion in the classic frame and the dot background is the same in both, up to 4 or 5 dva frame movement. With larger movements, the amount of perceived movement still linearly increases for the classic frame, more or less matching the actual movement, but drops for the dot background. However, in the range used for the frame effect, the amounts of perceived motion are the same in each type of stimulus.

We did not check the effect of the speed of motion on the amount of perceived motion.

In the limited dot-lifetime virtual aperture frames, the type of motion did not affect the amount of perceived motion, which was comparable to that in the other two types of stimuli.

The frame effect was only decreased in the limited dot-lifetime background stimuli. But in all other stimuli the frame effect was as strong as it was in the classic frame. This seems to indicate that the frame edges define the frame effect/illusion, and not the motion of the frame.

### Time-on-task

We inserted a few trials in 4 of the tasks that had various movement amplitudes (and different speeds given that they used the same movement durations) so that with a different random task order for each participant we can assess how the strength of the illusion varies across time-on-task. This would tell us if the brain learns to deal with the illusion (as it seems to be able to do with some other illusions) so that it has more veridical position information on the probes.

We used four epochs of 30 minutes in which illusion strength was assessed, but in Figure XXXX we can see no modulation of illusion strength across time, and a LME with Satterthwaite approximation confirms this impression. Bayesian statistics (Bayes Factor with non-informative prior) prives [moderate] support for the null hypothesis (BF10 = XXXX).

Taken together, all results on time suggest that the illusion is generated with immediately present stimuli and that over the course of 2 hours, the brain does not learn to deal with the illusion.

### Summary of results

Combined, these experiments suggest that the frame illusion relies on immediately present retinal position and motion from frame objects that are discernable from a background.

# Discussion

We find that the frame effect decreases with increasing distance between the frame and the flashed probes, that it requires the probes to be flashed while the frame is visible and that background motion does not evoke it, but any object - even with different internal motion - can serve as a frame. We also can not detect a decrease in the strength of the illusion over a period of 2 hours.

This could mean that the frame effect belies a low-level or early, possibly even innate, heuristic to estimate the position of objects relative to their local frame of reference.

This would predict that very young children and many other species would also be able to experience the frame effect, opening possibilities for future research into neural mechanisms for the perception of the position of objects in a constantly changing world.

# Conclusion

In conclusion, our work on the frame effect is awesome.

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