Comparisons of flash ILM, transformational apparent motion, and polarized gamma motion indicate these are three independent and separable illusions

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Abstract

Illusory line motion (ILM) refers to perceived motion in a bar when it is presented all at once. Explanations for ILM include low-level visual accounts, visual attention, and object tracking. These explanations tend to arise from studies using different protocols to induce ILM, based on the assumption that the same illusion is being generated. Using real motion in the same and in the opposite direction as the ILM quantifies the illusions from all protocols as the area between response curves for the left- and right-side inducers. This common measure enables testing of the assumption that two display configurations result in the same illusion. If there is a common underlying cause, an individual who shows a strong illusion in one situation should show a strong illusion in the other, but illusions that arise through different systems should not correlate. This approach has differentiated ILM induced by a flash (flash ILM) from ILM induced by matching the bar to an attribute of the inducing stimuli (*transformational apparent motion*, TAM). The former is thought to reflect attention, while the latter is thought to reflect object processing. Low-level visual explanations are often offered based on ILM that occurs when the bar is adjacent to only a single inducer (*polarized gamma motion*, PGM) rather than between two stimuli (flash ILM and TAM). The present study replicates the independence of flash ILM and TAM and shows that neither is related to PGM, suggesting that all three explanations for ILM are warranted and that the debates in the literature are conflating at least three different illusions.

Keywords Motion · Attention · Visual perception

Illusory line motion (ILM) refers to the perception of motion in a visual stimulus, usually a line or rectangular bar, that in reality appears all at once. The illusory motion usually takes the form of the bar appearing to shoot along its length in one direction, though in some configurations the bar may appear to shoot inward from both ends (von Grünau & Faubert, 1994).

ILM was first reported by Kanizsa, using displays in which the illusorily moving object (Kanizsa, 1951, 1979), hereafter referred to as the *bar*, suddenly appeared next to a stimulus, hereafter referred to as a *box*, that had been statically presented for an extended duration. The sudden onset of the bar was perceived as the bar expanding away from the box. Kanizsa referred to this illusory motion as *polarized gamma motion* (PGM; Kanizsa, 1951, 1979). PGM reverses direction in the

case of an existing bar offsetting, with the resulting perception being of the bar shrinking into the remaining adjacent box (as was mentioned by von Grünau & Faubert, 1994).

PGM was rediscovered by Hikosaka, Miyauchi, and Shimojo (1993b), who called it the *line motion illusion*, although in these displays the single box was presented only shortly before the presentation of the bar. As such, Hikosaka et al. (1993b) interpreted PGM as resulting from exogenous attention being initially directed to the onset of the box, so that the resulting attentional gradient (Laberge, 1983) created a series of visual onsets along the bar, with the end result being the perceived motion. The attentional explanation for PGM was also used to explain why ILM is also produced in displays in which the bar appears between two boxes shortly after one of the boxes has flashed. ILM in these displays takes the form of motion away from the flashed box (Hikosaka, Miyauchi, & Shimojo, 1993c), and here it is referred to as flash ILM. The theory that both protocols produce ILM as a result of exogenous attention suggests that PGM and flash ILM are essentially the same illusion that and the two protocols are essentially interchangeable.

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Other line motion illusions, such as *transformational apparent motion* (TAM), can also be produced using displays of two boxes and a bar, making them similar to the $\text{flash}_{\text{ILM}}$ protocol with the flash omitted. If the two boxes differ in color, for example, and the onset bar matches the color of one of the boxes, there is an illusion of motion away from the matching box (Hamm, 2017; Tse, Cavanagh, & Nakayama, 1998; Tse, 2006; von Grünau & Faubert, 1994), despite there being no initial flash to orient attention. This will be referred to as *colorTAM*, indicating that this is a TAM illusion, and the leading subscript indicates the conditions under which it was produced. Similarly, *shapeTAM* arises when two similarly sized rectangles replace the colored boxes, with one being horizontally elongated and the other vertically elongated. If the onset bar matches the height of one of the rectangles, the bar appears to shoot out of the size-matched rectangle (Corballis, Funnell, & Gazzaniga, 2002; Hamm, 2017; Tse, 2006). Indeed, a number of different attributes have been shown to produce this form of illusory motion (von Grünau & Faubert, 1994), in which TAM was referred to as *attribute priming*. Without the prior flash, TAM cannot be explained by the attentional gradient, because there is no way for attention to consistently orient to the matching box prior to the onset of the bar.

To effectively compare $\text{flash}_{\text{ILM}}$, TAM, and PGM, it is necessary to establish a standardized protocol that will result in a common metric to quantify the illusory percept. Steinman, Steinman, and Lehmkuhle (1995) have shown that presenting the bar over successive screen refreshes in the opposite direction from the illusory motion results in a reduced ability to discriminate the direction of the real motion. This general approach will be referred to as the *cancellation procedure*. Where Steinman et al. (1995) utilized PGM-type displays, cancellation of ILM through the use of real motion has been successfully implemented with both $\text{flash}_{\text{ILM}}$ (Ha, Li, Patten, & Hamm, 2018; Hamm, 2017; Han & Hamm, 2018; Han, Zhu, Corballis, & Hamm, 2016) and TAM (Hamm, 2017). With the direction of ILM being determined by the side of the single stimulus (PGM), the flash ($\text{flash}_{\text{ILM}}$), or the box with the matching attribute (TAM), the cancellation procedure results in a series of measurements over real-motion conditions for left- and right-side inducers. The measurements, referred to as *percept scores*, are calculated as the number of rightward-motion responses minus the number of leftward-motion responses, then divided by the total number of responses. This scoring procedure results in a guess-corrected value (Han et al., 2016). The area between the two series of percept scores (ILM_{area}) is then used to quantify the illusion. This metric is for all intents and purposes redundant with calculating the distance between the points of subjective equality that can be derived from the two series of percept scores over real-motion speeds, but it removes the complications that arise from determining what function should be fitted to the percept scores and what criterion should be used

to decide whether a given participant's data are well-fitted (see Han et al., 2016, for further discussion).

In the present investigation we employed the standardized protocols for display conditions, illusion quantification, and data analysis recommended by Han et al. (2016), which have been successfully employed and adhered to in a number of subsequent studies (Ha et al., 2018; Hamm, 2017; Han & Hamm, 2018). In other words, if two protocols are simply interchangeable methods for producing a common illusion, a participant's ILM_{area} from one protocol should predict their ILM_{area} from the other. However, if the illusions arise without a common underlying process, there is no reason to expect such a correlation, because the protocols are not invoking a common illusion. Essentially, if two protocols result in correlated values for ILM_{area} , this is viewed as evidence to support the conclusion that a shared underlying mechanism produces the illusory percept, and when two protocols do not result in correlated values for ILM_{area} , this is taken to indicate that the underlying mechanisms that produce the illusory percept are different and independent systems, and therefore the illusions are considered to be different, even if they may be perceptually similar in nature. Because of the theoretical implications of the null correlation, it is important to evaluate the evidence using Bayesian approaches, in addition to using null hypothesis significance testing to evaluate the accuracy of the alternative hypothesis that there is a common underlying mechanism. Even if one does not wish to draw inferences concerning the underlying mechanisms based upon this approach, if two protocols (i.e., flash vs. TAM vs. PGM) do not show a high test–retest reliability, this indicates that it is inappropriate to test theoretical claims derived from one protocol by using another; one cannot falsify a hypothesis using methods that do not produce related quantities in the first place. This is the basis for adopting an individual-differences experimental approach to investigate ILM (Han et al., 2016). As a final note, the use of individual differences to investigate underlying cognitive processes has been utilized for other illusory phenomenon (Ipser, Karlinski, & Freeman, 2018), as well as for investigating other mental operations, such as mental rotation (Searle & Hamm, 2012, 2016).

Adopting an individual-differences approach has established that the link between exogenously cued attention and $\text{flash}_{\text{ILM}}$ in that the magnitude of a participant's costs plus benefits during a cued discrimination task predicts the magnitude of the illusion, as indexed by ILM_{area} (Ha et al., 2018). This link has been further supported by the finding that the brain regions associated with exogenous attention and motion are active while participants view $\text{flash}_{\text{ILM}}$ displays (Hamm et al., 2014), as well as by the finding that a patient population with known deficits in attention have a reduced $\text{flash}_{\text{ILM}_{\text{area}}}$ relative to healthy controls (Crawford et al., 2010).

Although PGM displays—that is, the single box and bar with no flash paradigm—have also been suggested to arise

due to the attentional gradient (Hikosaka et al., 1993b), some properties of the illusory motion differ between PGM and flashILM . For example, whereas PGM reverses direction toward the inducing box when the existing bar offsets, in flashILM , offset bars continue to show motion away from the flashed box (Han et al., 2016). The onset and offset flash-induced illusions have also been shown to be correlated, meaning that a participant who shows a large onset bar illusion also shows a large offset illusion (Han et al., 2016), which is to be expected if the onset and offset versions are simply two ways to produce a common illusion. On the other hand, a slight change in the flash paradigm, in which the bar offsets during the flash rather than after it, does result in illusory motion toward the flash (*rILM*, hereafter). Notable is the fact that onset bars do not show *rILM* (Han et al., 2016). The $\text{rILM}_{\text{area}}$, however, is not predictive of $\text{flashILM}_{\text{area}}$, indicating that the area measure from participants does not simply always correlate. It also appears that under appropriate conditions, both *rILM* and flashILM may occur simultaneously, and given their opposite directions, will tend to interfere or cancel each other (Han & Hamm, 2018). In short, *rILM* and flashILM , although both forms of illusory motion, appear to be independent and separable illusions.

Similar to how measures of onset and offset flashILM are correlated (Han et al., 2016), it has been shown that area measures of colorTAM and shapeTAM are also predictive of each other, consistent with the interpretation that these two TAM illusions are two forms of the same illusion arising from object processing (Tse et al., 1998; Tse, 2006). However, the area measure for neither of these TAM illusions was predictive of flashILM 's area, suggesting that TAM and flashILM are two different illusions, requiring separate explanations (Hamm, 2017). Furthering this suggestion is the fact that TAM-type displays have been shown to activate object and motion regions of the brain (Tse, 2006), rather than the attention and motion regions activated by flashILM displays (Hamm et al., 2014). Finally, it appears that the TAM and flashILM illusions can both arise in the same displays and can either accentuate or interfere with motion perception when the illusions are induced in the same or in opposite directions (Hamm, 2017). In short, adopting the individual-differences approach and using the cancellation method to obtain an area measure as an index of the illusion has produced a pattern of results that is consistent with other evidence that flashILM and TAM are different illusions. Moreover, this approach has produced evidence consistent with the involvement of exogenous attention in generating flashILM .

With PGM showing a reversal of direction with offset bars (von Grünau & Faubert, 1994) whereas flashILM does not (Han et al., 2016), this makes some aspects of PGM similar to TAM-type illusions, which also reverse direction with offset bars (Tse, 2006). On the other hand, PGM may arise due to the spreading of subthreshold activity in visual cortical areas

(Jancke, Chavane, Naarman, & Girinvald, 2004), rather than through the object-processing areas thought to be responsible for TAM (Tse, 2006).

It is possible that PGM could be a combination of flashILM and TAM. PGM displays, with a single box presented away from the fixation, have been argued to capture exogenous attention, and therefore the resulting illusion has been interpreted as being reflective of attentional gradient, as per flashILM . However, because the onset of the bar could be interpreted as the inducing box changing shape, particularly when the box and bar are of the same height, the PGM display also suggests an interpretation based on TAM. Given that TAM and the attentional gradient are not mutually exclusive explanations, both could contribute to the illusory motion, making PGM a combination of flashILM and TAM with or without contributing input from early visual cortical areas (Jancke et al., 2004). In studies in which flashILM and TAM conditions have both been met, it has been found that both processes contribute and increase the overall illusion (Hamm, 2017). PGM displays could likewise reflect this dual input. Multiple regression analysis can be used to separate the contributions of flashILM and TAM, since each explains a separate portion of the ILM_{area} measure's variance. On the other hand, low-level spreading of subthreshold activation in visual cortex (Jancke et al., 2004) has also been suggested for PGM-type displays and could be sufficient to explain PGM, without any contribution from either attention or object processing. This allows for the possibility that PGM arises for entirely separate reasons from either flashILM or TAM. Such an explanation would also account for why, in the absence of a flash, bars presented between two boxes appear to originate near both boxes so that the motion "crashes" in the middle (Faubert & von Grünau, 1995). It is critical that PGM be investigated to determine which of these situations is the case.

We used the cancellation paradigm to quantify the illusion as the area between the percept functions for left- and right-sided inducers (Ha et al., 2018; Hamm, 2017; Han & Hamm, 2018; Han et al., 2016), for standard flashILM , TAM, and PGM displays. Since flashILM has sometimes involved presenting two boxes with the bar visible, with the illusion being a perception, when the bar changes color, of the color spreading over the bar away from the flash (Crawford, Kean, Klein, & Hamm, 2006), this protocol will also be included. We did this primarily to ensure that at least two conditions would be predicted to be highly related, since there was no a priori reason to expect that flashILM and what we will refer to as paintILM would arise for different reasons. This would ensure that, should PGM be found to be unrelated to both flashILM and TAM, in support of the explanation featuring low-level spreading of subthreshold activation (Jancke et al., 2004), and should the lack of a relationship between TAM and flashILM (Hamm, 2017) also be replicated, the consistency of the two ILM illusions would demonstrate that, when the

illusions were expected to arise for the same reason, the methods employed here were capable of detecting such a relationship.

In addition to ILM_{area} , the cancellation procedure also allows the examination of decision times as a function of distance from the point of subjective equality. Previous studies have shown that decision times are described by a distance decay function (Ha et al., 2018; Hamm, 2017; Han & Hamm, 2018; Han et al., 2016). The tendency for decisions to slow as the condition approaches the point of subjective equality indicates that the illusory and real motion are cancelling and are not consistent with the point of subjective equality reflecting the case in which either the real or the illusory motion is being perceived with equal probability (Hamm, 2017; Han & Hamm, 2018; Han et al., 2016). In addition, the decision time congruency effect (dt_{ce}) is the difference in response times between conditions in which the real and illusory motion are in the same direction and conditions in which the illusory and real motion are in opposite directions. This measure is thought to be primarily reflective of decision- and response-based processes that arise after the generation of the motion signal, rather than of the processes responsible for the illusory motion itself (Han et al., 2016).

Method

Participants

Participants were recruited from among the University of Auckland undergraduate participant pool and volunteers from the undergraduate and postgraduate student body. Data were collected from 42 participants in order to reach the predetermined sample size of 36 complete data sets. Participants were dropped from the study for the following reasons: Three discontinued during the experiment, one reversed the response keys, one misunderstood the instructions with regard to equating the luminance of the stimuli and set the green luminance to black, and one indicated during debriefing that he or she had spent much of the time during the procedure trying to work out how the experiment worked. The data set for this last exclusion was replaced on the grounds that the participant's performance was unlikely to accurately represent their motion perception and/or decision times, since the participant was not concentrating fully on the task. All reported normal or corrected-to-normal vision, and none reported any color deficiency. As a result, only the data from the 36 participants who completed the experiment without technical errors were included in the analysis (six male, 30 female; mean age = 22.06, $SD = 5.33$; 33 right-handed, three left-handed, as assessed by the Edinburgh Inventory: Oldfield, 1971). Participants gave written informed consent prior to participation, and all procedures were approved by the

University of Auckland's Human Participants Ethics Committee (protocol number: 8593).

Apparatus

The experimental program was written in Borland Pascal 7.0 and run under Windows 98 on a Pentium III computer (450-MHz CPU) rebooted in DOS mode, to ensure accurate millisecond timing (Myors, 1999). The millisecond-timing routines are those described in Hamm (2001), and synchronization with the screen refresh cycle employed routines described by Heathcote (1988). Stimuli were presented on a Philips CRT monitor with a 60-Hz refresh cycle at a screen resolution of 640×480 pixels, with color settings ranging from 0 to 63. The experiment was conducted in a well-lit room with the experimenter situated outside the testing room. We calculated the mean of three luminance readings, taken under the same lighting conditions as the data collection by a Konica Minolta LS-100 at every fifth RGB setting from 0 to 60, and again at RGB setting 63, and fitted these means to a polynomial equation (all produced R^2 values $> .99$) to convert the RGB settings to candles per square meter for gray, red, and green separately. Responses were made on the "<" and ">" keys of a standard keyboard and were detected using routines suggested by Brysbaert (1990).

During the setting of the luminance levels for the green and the gray boxes, adjustments of luminance were made on the number pad using the "4" and "5" keys, respectively, to decrease or increase the RGB settings in steps of five, and the "1" and "2" keys, respectively, to decrease and increase the RGB settings by one.

Stimuli

The dimensions and relative positions of the stimulus items may be seen in Fig. 1. The background was a uniform neutral gray (27.7 cd/m^2). The fixation cross was black (10.7 cd/m^2). The boxes during the $flashILM$, $paintILM$, and PGM trials were

Fig. 1 Diagram of the display, indicating the size and relative locations of stimuli in degrees of visual angle; not drawn to scale

darker gray (average 18.2 cd/m^2 , $SD = 1.61$), whereas the boxes during the colorTAM trials were red (17.5 cd/m^2) and green (average luminance of 18.4 cd/m^2 , $SD = 1.73$). During the paintILM trials, the boxes were joined by a gray bar (average luminance of 22.9 cd/m^2 , $SD = 0.80$). During the flashILM and paintILM trials, the luminance of the flash was 49.8 cd/m^2 .

Procedure

Participants completed the Edinburg Handedness Inventory (Oldfield, 1971) and were instructed to make all responses using the index and middle fingers of their dominant hand; ambidextrous participants were instructed to use their preferred hand.

Setting of luminance The luminance differences between the dark gray, red, and green boxes were minimized following the same procedure described in Hamm (2017), which is based on the procedure described by Troscianko and Low (1985). The procedure began with a red square ($4.82^\circ \times 4.82^\circ$ 17.5 cd/m^2) in the middle of a green background (81.9 cd/m^2). Every 50 ms, the square changed to green and the background to red. The participant adjusted the RGB setting for green until the flickering was subjectively determined by them to be at a minimum. Once this was achieved (mean luminance setting for green = 18.4 cd/m^2 , $SD = 1.73$), the third color, gray, was introduced, and the square and background cycled through the three colors. Adjustments were now made to adjust the luminance of gray (mean luminance setting for gray = 18.2 cd/m^2 , $SD = 1.61$). These RGB settings were then used for the gray, red, and green starting boxes and the ILM bars. The initial bar during the paintILM trials was presented using the RGB setting as close as possible to halfway between the background (27.7 cd/m^2) and the individual participant's setting for gray (mean luminance setting for starting paint bar = 22.9 cd/m^2 , $SD = 0.80$).

Trial sequence A trial began with the presentation of a black fixation cross (10.7 cd/m^2) for 500 ms. This was followed by the presentation of the boxes, the configuration of which depended upon the trial type. During flashILM , paintILM , and colorTAM trials, the configuration consisted of two boxes, one on the left and one on the right. On PGM trials, only one box, on either the left or the right, was presented. On paintILM trials, the boxes were joined by a gray bar, which differed in luminance from both the boxes and the background. On colorTAM trials, one box was red and the other green, counterbalanced so that on half the trials the red box was on the left. On flashILM and PGM trials, the boxes were gray. This display was presented for 500 ms.

This was followed by a 50-ms interval, which on flashILM and paintILM trials involved the brightening (to 49.8 cd/m^2) of either the left or the right box, counterbalanced for side. The flashed box returned to its starting luminance after this

interval. On colorTAM and PGM trials, no change in the display occurred.

On flashILM and PGM trials, the bar was gray and of the same luminance as the box(es). On colorTAM and paintILM trials, the bar was, with equal probability, either red or green. On colorTAM trials, the bar matched the color of the left box on half the trials, and the color of the right box on half the trials. The bar was presented either all at once (no real motion), in halves over two screen refresh cycles (fast motion), in thirds over three screen refresh cycles (medium motion), or in quarters over four screen refresh cycles (slow motion). When there was motion, half the time it was from left to right, and half the time from right to left. Decision times were measured from the onset of the first segment of the bar to appear until the participant's response.

The display remained visible until the participant had indicated by button press the direction of the motion. Half of the participants pressed the "<" or the ">" key on the keyboard to indicate the bar appeared to move toward the left or the right, respectively, and the other half pressed the "<" or ">" key on the keyboard to indicate that the bar came from the left or the right, respectively. Upon response all display items were removed, and a blank screen was presented during the 1,000-ms intertrial interval.

There were 140 trials for each of the flashILM , paintILM , colorTAM , and PGM conditions, for a total of 560 trials. Within each illusion type, there were equal numbers of trials for the seven conditions of real motion (slow left, medium left, fast left, no motion, fast right, medium right, and slow right), divided equally between left and right inducers. The inducers were flashes (flashILM and paintILM trials), the box that matched the bar color (colorTAM trials), or the single box (PGM trials). Effectively, the sides of the illusion inducer and of real motion were counterbalanced over the 140 trials of each trial type.

Examples of the trial sequences can be seen in Fig. 2, illustrating each of the trial types, and depicting a different speed of leftward motion for each as an example.

Results

A statistical analysis was performed to evaluate the accuracy of predictions derived from the null hypothesis. The prediction from the null hypothesis was considered inaccurate if the observed data were likely to be observed less than 5% of the time if the null hypothesis were true. In addition, the weight of the evidence for and against the null hypothesis was evaluated by means of the Bayesian $p_{H0|D}$ value, which is considered the probability of the null given the data using descriptions derived from Raftery (1995), including the range suggested to reflect equivocal evidence (Ha et al., 2018), as is listed in Table 1. Correlation coefficients (Masson, 2011) and t values

Fig. 2 Depiction of the trial sequence, using the presentation of no motion, fast motion, medium motion, and slow motion to the left from flashILM , paintILM , colourTAM , and PGM displays, respectively. In the depicted examples, illusory and real motion would be predicted to be in opposition. The timing for responses, and the 4,000-ms maximum duration, all begin at the frame in which the first segment of the bar is presented, as indicated by the asterisks. Note that, although different

shades of gray are used to represent the red and green boxes in the colourTAM displays, participants set the luminance of these colors to appear as similar to each other as possible. Dark gray is used to represent the change in bar color during the paintILM trials; the new color could be either red or green of a similar luminance to the colors in the flanking boxes. The initial bar in that condition was set to be gray at a luminance between those of the background and the initial boxes

Table 1 Ranges and descriptions for $p_{H0}|D$, derived from Raftery (1995) and including the equivocal range from Ha et al. (2018)

$p_{H0} D$		Description
Min	Max	
.99 ⁺	1.00	Very strong evidence in favor of the null hypothesis
.95 ⁺	.99	Strong evidence in favor of the null hypothesis
.75 ⁺	.95	Positive evidence in favor of the null hypothesis
.525 ⁺	.75	Weak evidence in favor of the null hypothesis
.475	.525	Equivocal; equally supportive of H0 and H1
.25	.475 ⁻	Weak evidence against the null hypothesis
.05	.25 ⁻	Positive evidence against the null hypothesis
.01	.05 ⁻	Strong evidence against the null hypothesis
.00	.01 ⁻	Very strong evidence against the null hypothesis

H0: null hypothesis; H1: alternative hypothesis

(Rouder, Speckman, Sun, Morey, & Iverson, 2009) can be converted to Bayes factors (BF), and these odds ratios were converted to $p_{H0}|D$ via $p_{H0}|D = \text{BF}/(1 + \text{BF})$ (Masson, 2011), which are expressed as the probability of the null given the data.

Percept scores

The area measure for each illusion condition was first subjected to a single-sample *t* test to verify that the measure differed from zero, in order to verify the presence of an illusion. All conditions resulted in very strong evidence against the null hypothesis, with all $t(35) \geq 12.40$, $p < .001$, $p_{H0}|D < .01$, and mean areas (with standard deviations) of 3.73 (1.80), 5.71 (1.56), 4.69 (2.09), and 7.54 (1.71), for TAM, PGM, flashILM , and paintILM , respectively. The mean areas for

flashILM and TAM were compared to those obtained in Hamm (2017), in which similar displays had been employed, and the present values did not differ from those previously reported [$\mu = 4.149$, $t(35) = 1.56$, $p = .13$, $p_{H0}|D = .64$, for flashILM , and $\mu = 3.296$, $t(35) = 1.44$, $p = .16$, $p_{H0}|D = .68$, for TAM, both showing weak evidence in favor of the null hypothesis].

In addition, the mean areas for each illusion type was compared between those participants who responded by indicating where the bar appeared to go and those participants who responded by indicating where the bar appeared to come from. This resulted in a nonsignificant difference for TAM [$t(34) = 0.69$, $p = .50$, $p_{H0}|D = .82$, positive evidence in favor of the null hypothesis; $M = 3.52$ vs. 3.93 , where from vs. where to, respectively]. There was also a nonsignificant difference for PGM [$t(34) = 0.98$, $p = .33$, $p_{H0}|D = .78$, positive evidence in favor of the null hypothesis; $M = 5.46$ vs. 5.97 , where from vs. where to, respectively]. There was a nonsignificant difference for flashILM [$t(34) = 1.47$, $p = .15$, $p_{H0}|D = .66$, weak evidence in favor of the null hypothesis; $M = 5.20$ vs. 4.19 , where from vs. where to, respectively]. Finally, there was a nonsignificant difference for paintILM [$t(34) = 1.08$, $p = .28$, $p_{H0}|D = .77$, positive evidence in favor of the null hypothesis; $M = 7.85$ vs. 7.23 , where from vs. where to, respectively]. Moreover, since the group by illusion interaction was not significant in a two-way mixed-factor analysis of variance (ANOVA) [$F(3, 102) = 2.03$, $p = .114$, $MSE = 2.52$, $p_{H0}|D = .68$, weak evidence in favor of the null hypothesis], the response option was not considered further in subsequent analyses.

Relationships between illusion area measures

The mean percept scores for left- and right-side inducers producing flashILM , TAM, paintILM , and PGM may be seen in Fig. 3. The area between the left and right curves for each illusion type was quantified for each individual participant by first calculating the area under the left and right curves separately, and then subtracting the area under the right curve from the area under the left. If the direction of the illusion were to reverse, and be toward the inducer, this order of the calculation would result in a negative value, allowing one to infer the direction of illusory motion from the measurement rather than to presume the direction a priori.

Individual participants' area measures were then correlated between conditions, excluding any data that had overly influenced the correlation, as indexed by a Cook's D value greater than $4/n = 0.11$. This analysis revealed that flashILM and paintILM were correlated [$r(31) = .73$, $p < .01$, $p_{H0}|D < .01$, very strong evidence against the null hypothesis; see Fig. 4a]. When the three outliers were included, the same result was found [$r(34) = .72$, $p < .01$, $p_{H0}|D < .01$]. This finding replicates the strong relationship between the area measures from conditions that produce a common illusion (Hamm, 2017; Han & Hamm, 2018; Han et al., 2016).

In contrast, TAM was correlated with neither flashILM [$r(30) = -.05$, $p = .80$, $p_{H0}|D = .85$, positive evidence in favor of the null hypothesis; see Fig. 4b] nor paintILM [$r(32) = .06$, $p = .73$, $p_{H0}|D = .85$, positive evidence in favor of the null hypothesis; see Fig. 4f]. When the four and two outliers, respectively, were included, the conclusions did not change, with $r(34) = -.03$, $p = .85$, $p_{H0}|D = .85$, and $r(34) = .01$, $p = .95$, $p_{H0}|D = .86$, for flashILM and paintILM , respectively. This finding replicates the lack of a correlation between TAM and attention-based forms of ILM (Hamm, 2017).

Furthermore, PGM was not correlated with flashILM [$r(32) = .17$, $p = .33$, $p_{H0}|D = .78$; positive evidence in favor of the null hypothesis], TAM [$r(33) = .19$, $p = .28$, $p_{H0}|D = .76$; positive evidence in favor of the null hypothesis], or paintILM [$r(32) = .12$, $p = .49$, $p_{H0}|D = .82$; positive evidence in favor of the null hypothesis]. Again, when the two, one, and two respective outliers were included, the conclusions were the same for PGM's correlations with flashILM , TAM, and paintILM , with $r(34) = .23$, $p = .18$, $p_{H0}|D = .70$, weak evidence in favor of the null hypothesis; and $r(34) = .12$, $p = .48$, $p_{H0}|D = .82$, and $r(34) = .16$, $p = .3643$, $p_{H0}|D = .79$, respectively, both positive evidence in favor of the null hypothesis.

Decision times

The mean decision times for each illusion condition as a function of real motion for the left- and right-side inducers can be seen in Fig. 5. When decision times are plotted as a function of the distance from the point of subjective equality, they are described by a distance decay function, shown in Fig. 6, for each condition individually (see Fig. 6a–d) and when all conditions are combined (Fig. 6e).

The decision time congruency effect (dt_{ce}) was calculated for each illusion condition by averaging all conditions in which the illusory and real motions would be expected to be in opposite directions (incompatible condition), and separately averaging all conditions in which the two motions would be expected to be in the same direction (compatible condition). The no-real-motion condition was not included in either of these calculations. The dt_{ce} is the difference between the incompatible and compatible conditions.

The dt_{ce} values were significant for flashILM [$t(35) = 12.29$, $p < .001$, $p_{H0}|D < .01$, $M = 165.45$ (80.8)], TAM [$t(35) = 7.57$, $p < .001$, $p_{H0}|D < .01$, $M = 147.09$ (116.65)], paintILM [$t(35) = 8.48$, $p < .001$, $p_{H0}|D < .01$, $M = 142.92$ (101.08)], and PGM [$t(35) = 9.38$, $p < .001$, $p_{H0}|D < .01$, $M = 189.54$ (121.21)], with all showing very strong evidence against the null hypothesis.

As with the area measure, the means of the dt_{ce} for each illusion type were compared for those participants who

Fig. 3 Mean percept scores as a function of real-motion condition, following a left-side (solid lines with filled squares) or a right-side (dashed line with open circles) inducer for (A) flashILM , (B) TAM, (C) paintILM ,

and (D) PGM. The area measure quantifies the area between the left and right curves

responded to indicate where the bar appeared to go to and those participants who responded where the bar appeared to come from. This resulted in a nonsignificant difference for TAM [$t(34) = 0.34$, $p = .73$, $p_{H0}|D = .85$, positive evidence in favor of the null hypothesis; $M = 140$ vs. 154, where from vs. where to, respectively]. There was also a nonsignificant difference for PGM [$t(34) = 1.45$, $p = .16$, $p_{H0}|D = .67$, weak evidence in favor of the null hypothesis; $M = 161$ vs. 218, where from vs. where to, respectively]. There was a nonsignificant difference for flashILM [$t(34) = 0.04$, $p = .97$, $p_{H0}|D = .86$, positive evidence in favor of the null hypothesis; $M = 165$ vs. 166, where from vs. where to, respectively]. And there was a nonsignificant difference for paintILM [$t(34) = 0.52$, $p = .61$, $p_{H0}|D = .84$, positive evidence in favor of the null hypothesis; $M = 134$ vs. 152, where from vs. where to, respectively]. Moreover, since the group by illusion interaction was not significant in a two-way mixed factor ANOVA [$F(3, 102) = 1.22$, $p = .307$, $MSE = 4,461.89$, $p_{H0}|D = .76$, positive evidence in

favor of the null hypothesis], the response option was not considered further in the subsequent analyses.

The dt_{ce} and the area measure for each illusion were tested by correlation to determine whether they were related. The scatterplots may be seen in Fig. 7. After discarding data with excessive Cook's D values, this analysis resulted in a significant correlation for flashILM [$r(32) = .37$, $p = .0322$, $p_{H0}|D = .33$; weak evidence against the null hypothesis; two outliers], which was not significant if the extreme scores were included [$r(34) = .20$, $p = .2488$, $p_{H0}|D = .75$; weak/positive evidence in favor of the null hypothesis]. As with flashILM , paintILM showed a significant relationship [$r(31) = .36$, $p = .04$, $p_{H0}|D = .38$; weak evidence against the null hypothesis; three outliers], which was not significant if the extreme scores were included [$r(34) = .1$, $p = .56$, $p_{H0}|D = .83$; positive evidence in favor of the null hypothesis]. TAM showed a relationship between the area measure and the dt_{ce} [$r(30) = .43$, $p = .014$, $p_{H0}|D = .17$; positive evidence against the null hypothesis;

Fig. 4 Correlations between an individual participant's area measures between (A) flashILM and paintILM, (B) TAM and flashILM, (C) flashILM and PGM, (D) TAM and PGM, (E) paintILM and PGM, and (F) TAM and paintILM. Open symbols indicate data pairs deemed to be outliers on the basis of Cook's D

four outliers], even when the extreme scores were included [$r(34) = .48$, $p < .01$, $p_{H0}|D = .06$; positive evidence against the null hypothesis]. Finally, PGM did not show a significant relationship when the extreme scores were excluded [$r(31) = .31$, $p = .08$, $p_{H0}|D = .53$; equivocal/weak evidence in favor of the null hypothesis; three outliers] nor when they were

included [$r(34) = .22$, $p = .20$, $p_{H0}|D = .71$; weak evidence in favor of the null hypothesis].

As with the area measure, the dt_{ce} was tested for relationships between the conditions. The scatterplots may be seen in Fig. 8. This shows a significant relationship between flashILM and paintILM [$r(32) = .77$, $p < .01$, $p_{H0}|D < .01$; very strong

Fig. 5 Mean decision times as a function of real-motion condition, following a left-side (solid lines with filled squares) or a right-side (dashed line with open circles) inducer for (A) *flashILM*, (B) *TAM*, (C) *paintILM*, and (D) *PGM*. The decision time congruency effect is the difference in mean response times between conditions in which the real motion and

illusory motion are thought to conflict (left inducer in real-motion conditions -3 , -2 , and -1 , and right inducer in real-motion conditions 1 , 2 , and 3) and those in which the real motion and illusory motion are thought to combine (left inducer in real-motion conditions 1 , 2 , and 3 , and right inducer in real-motion conditions -3 , -2 , and -1)

evidence against the null hypothesis; two outliers], which remained when the extreme scores were retained [$r(34) = .64$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis]. We found a significant correlation between *TAM* and *flashILM* [$r(33) = .43$, $p = .01$, $p_{H0}|D = .15$; positive evidence against the null hypothesis; one outlier], which remained when the one extreme score was included [$r(34) = .37$, $p = .03$, $p_{H0}|D = .31$; weak evidence against the null hypothesis]. There was a significant correlation between *flashILM* and *PGM* [$r(31) = .70$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis; three outliers], which remained when the extreme scores were included [$r(34) = .59$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis]. Next, there was a significant correlation between *TAM* and *PGM* [$r(32) = .50$, $p < .01$, $p_{H0}|D = .04$; strong evidence against the null hypothesis; two outliers], which remained when the extreme scores were included

[$r(34) = .57$, $p < .01$, $p_{H0}|D = .01$; strong/very strong evidence against the null hypothesis]. There was a significant correlation between *paintILM* and *PGM* [$r(34) = .79$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis; no outliers]. And finally, there was a significant correlation between *TAM* and *paintILM* [$r(32) = .72$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis; two outliers], which remained when the extreme scores were included [$r(34) = .72$, $p < .01$, $p_{H0}|D < .01$; very strong evidence against the null hypothesis].

The dt_{ce} does not involve the decision times to purely illusory motion that arises when there is no real motion in the display (real motion = 0). Combining left and right illusory motions, the decision times for *flashILM* and *paintILM* were compared and found not to differ significantly [$t(35) = 1.52$, $p = .14$, $p_{H0}|D = .66$, weak evidence in support of the null hypothesis; means of 632 and 598 ms, respectively]. These

Fig. 6 Decision times plotted as a distance decay function from the point of subjective equality for (A) flashILM , (B) TAM, (C) paintILM , (D) PGM, and (E) all conditions combined. Open symbols indicate data deemed to be outliers due to excessive Cook's D values

were combined, and the mean decision time for flash-based illusions (615 ms) was compared to the decision times for both TAM (mean 699 ms) [$t(35) = 6.15$, $p < .01$, $p_{H0}|D < .01$, very strong evidence against the null] and PGM (mean 551 ms) [$t(35) = 3.73$, $p < .01$, $p_{H0}|D = .014$, strong evidence against the null].

Discussion

All displays produced illusions, as quantified by the area measure obtained using the cancellation technique. In addition, the magnitude of the effects for flashILM and TAM were similar to the magnitudes that had been found before under similar experimental conditions (Hamm, 2017). However, the present study did not replicate the finding that the area measure was

larger when participants responded to indicate where the motion came from rather than where the motion went to, suggesting that this effect may be unreliable. The strong relationship between the area measures of conditions in which the illusion is thought to arise for a common reason was again shown when comparing flashILM and paintILM , replicating the high test–retest reliability of $\text{flashILM}_{\text{area}}$ that had been shown when comparing onset and offset versions of flashILM (Han et al., 2016). Similarly, TAM has also been shown to have high test–retest reliability between different versions of TAM, namely colorTAM and shapeTAM (Hamm, 2017), so the present lack of a relationship between flashILM and TAM cannot be attributed to poor test–retest reliability of either illusion, per se. Moreover, this lack of a correlation between flashILM and TAM replicates the independence between these illusions that has been previously reported (Hamm, 2017). Not only did the

Fig. 7 Correlations between ILM_{area} and the dt_{ce} for (A) flashILM, (B) TAM, (C) paintILM, and (D) PGM. Open symbols indicate data deemed to be outliers due to excessive Cook's *D* values

present data fail to reject the null hypothesis, which states that flashILM and TAM are independent, the Bayesian analysis supports the argument that independence is more supported by the data than is the alternative. Additionally, paintILM was also found to be unrelated to TAM. This finding is considered another replication of the independence between flashILM and TAM, given the strong connection between flashILM and paintILM, both empirically and theoretically. These findings provide further empirical support for the argument that independent explanations are required in order to explain the illusions referred to as flashILM and TAM. This supports the literature that explains flashILM and paintILM as resulting from exogenous attention, and also the literature that indicates that TAM arises due to an impletion-type process (Downing & Treisman, 1997) as objects are tracked over time.

Having ensured that previous findings of high test–retest reliability between expected conditions were found (flashILM and paintILM), and also replicating previous findings of independence between flashILM and TAM, as well as replicating this independence with paintILM and TAM, the primary question of interest in the present study was with regard to PGM. To reiterate, PGM has been suggested to be reflective of exogenous visual attention (Hikosaka, Miyauchi, & Shimojo, 1993a), yet the displays could very well be expected to evoke TAM-related processes, as well. It is possible that the PGM display could invoke both of these processes, resulting in

PGM being a compound illusion influenced by both attention and object processing in combination. TAM and flashILM have been shown to combine, or conflict, with each independently, contributing to the final motion percept (Hamm, 2017), and PGM displays may be a situation in which such interaction arises. PGM has, however, also been explained as arising due to the spreading of subthreshold activation in early cortical areas that surround a visual stimulus (Jancke et al., 2004), which explains PGM without reference to either exogenous visual attention or object tracking.

The present findings showed PGM to be unrelated to either of the attention-based illusions (flashILM and paintILM), and also unrelated to TAM. This finding that PGM is independent of both attention-based and object-based illusions is therefore most consistent with the literature that explains PGM as being due to early visual subthreshold spreading of activity (Jancke et al., 2004), making PGM a third form of illusory line motion. Although much of the literature has focused upon attempting to find a single, unitary explanation for all forms of ILM, the failure to find consensus appears to reflect the conflation of a number of different illusions that are perceptually similar but that arise for independent reasons. So while the conclusion that attention is not necessary to explain PGM is upheld, the extrapolation of that conclusion to suggest that attention never results in, or does not contribute to, ILM is unfounded. Moreover, attention simply cannot explain ILM under TAM

Fig. 8 Correlations for the dt_{ce} , in milliseconds, between the conditions (A) $flash_{ILM}$ and $paint_{ILM}$, (B) TAM and $flash_{ILM}$, (C) $flash_{ILM}$ and PGM , (D) TAM and PGM , (E) $paint_{ILM}$ and PGM , and (F) TAM and $paint_{ILM}$. Open symbols indicate data deemed to be outliers due to excessive Cook's D values

display arrangements, such as the present $color_{TAM}$ configurations and previous $shape_{TAM}$ displays (Corballis et al., 2002; Hamm, 2017; Tse, 2006). However, if $flash_{ILM}$ arises for a different reason than TAM , then it does not follow that attention cannot be the explanation for ILM under the $flash_{ILM}$ paradigm. In addition, although the displays used in PGM paradigms may afford themselves to interpretations based on object tracking (TAM) or attention ($flash_{ILM}$), either separately or in combination, these theoretical links were not empirically supported by the present results. Therefore, discussions in the literature of results derived from PGM -type displays do

not appear to inform us as to the nature of either object tracking or exogenous attention.

The implications of these findings are that previous interpretations, such as the notion that attention shows a center-surround-type arrangement (Steinman et al., 1995), which were derived from PGM -type displays, may require reinterpretation to suggest that it is the influence of spreading subthreshold activation, rather than exogenous visual attention, that this configuration induces. In addition, recent studies examining the influence of stimulus onset asynchrony (SOA) on rating of the velocity and strength of ILM (Hubbard & Ruppel, 2018)

may not be reflective of an attention-based illusion, but may again be indexing aspects of this illusion based on spreading subthreshold activation. Whether or not TAM and/or flash ILM would show similar patterns of rating changes over SOA is an empirical question. Although the area measure suggests that individual participants' ratings for the different illusions would not be correlated, the rating scales may also be reflective of an individual's decision-making processes, and the dt_{ce} suggests that measures that reflect decision-making postmotion perception may capture that aspect of an individual's performance. In short, rating scales may capture aspects about the perceived motion rather than of the mechanisms or processes that lead to the production of the motion.

It must also be considered that some previous findings using PGM displays may indeed reflect a compound illusion, particularly when the presentation of the single box occurs in very close temporal proximity to the presentation of the bar. In such paradigms, it is possible that both attention and early visual activity contribute to the illusory motion percept, whereas at longer box–bar SOAs the illusion may reflect less input from attention, as the exogenous gradient is thought to fade over time. If attention and the influence of spreading early visual activity have different time courses—and there is no reason to expect them to be identical—it would require focused experimentation to tease these influences apart. However, before doing so it would be necessary to determine whether this speculated compound nature of the illusions is even warranted. Although flash ILM and TAM have been shown to combine (Hamm, 2017), it has not yet been determined whether, or under what circumstances, PGM combines with either TAM or flash ILM . There is some suggestion that PGM and attention-based illusions may combine, since it has been suggested that ILM may have contributions from both a preattentive mechanism and attention itself (von Grünau, Dube, & Kwas, 1996), and those results could easily be explained by a combination of early visual processes (PGM) and attention (flash ILM ; although in this study, attention was captured by a singleton, not a luminance flash). Until this is determined, given the demonstrated independence of PGM and flash ILM , and given the relationship between flash ILM and other measures of visual attention, such as the costs plus benefits of visual cuing (Ha et al., 2018), studies using PGM-type displays should be interpreted in terms of the spread of early visual cortical activity rather than in terms of exogenous visual attention, whereas studies using two boxes and flashes should be interpreted in terms of exogenous visual attention and not in terms of early visual effects. Finally, displays in which the two boxes differ and motion is generated by matching the bar to one of the boxes should be considered reflective of object tracking rather than either the spreading of early visual cortical activity or exogenous visual attention. Many of the interpretations found in the literature will otherwise continue to hold, albeit they may require rephrasing to correspond to the appropriate system that appears to be

responsible for generating the illusory motion. Also, any arguments concerning the interpretation of findings from studies that employ displays that differ from those used in a given article should be set aside as unwarranted; effectively, studies that employ PGM-type displays cannot provide evidence for or against the interpretations offered in studies that employ TAM and/or flash ILM displays, and so on.

Moreover, what measure one uses to quantify ILM must be considered carefully. For example, in the present study, the decision time congruency effect was also found for all conditions. This measure was at best only weakly related to the ILM_{area} measures. Unlike the ILM_{area} measure, the dt_{ce} was found to be correlated between all conditions. The dt_{ce} , however, has been suggested to primarily reflect decision processes (Han et al., 2016). Given that the decision in this task concerned motion, the dt_{ce} appears to primarily reflect influences after the illusory motion has been generated, and so is likely to have its influence on response decision processes rather than to be reflective of how the illusory motion is generated per se. This is not a controversial suggestion, given that response time data will be influenced by processes from stimulus presentation all the way through to the execution of responses (Jensen, 2006). However, it offers the possibility that the area measure is best suited to addressing questions of the processes that arise in illusory motion, whereas the dt_{ce} is best suited to addressing questions concerning aspects of decisions about motion perception, regardless of how the motion signal is generated.

With this in mind, it becomes a basic necessity to establish the relationship between the various measures employed to quantify effects in the ILM literature. These have ranged from the area measure, as obtained from the present cancellation paradigm (Ha et al., 2018; Hamm, 2017; Han & Hamm, 2018; Han et al., 2016); the proportion of trials in which responses indicate motion away from an inducer, in paradigms in which no real motion is employed (Hikosaka et al., 1993a, 1993b, 1993c; von Grünau & Faubert, 1994); and ratings of the velocity and/or strength of illusory motion (Hubbard & Ruppel, 2011, 2018), or of combined illusory and real motion (Christie, 2014; Christie & Klein, 2005). It is certainly a strength to be able to investigate a phenomenon using a wide range of paradigms and measures, but it is also a basic necessity to establish the relationship, if any, between the paradigms (as in the present study) and also between the measures employed (Han et al., 2016). If, as with the area and dt_{ce} measures, that relationship is weak at best, then generalizing conclusions between studies becomes problematic, given that different measurements will be sensitive to different collections of processes. For example, given the weak association between ILM_{area} and the dt_{ce} , and given that these quantities sometimes have shown to be correlated (Ha et al., 2018), sometimes have not (Han et al., 2016), and sometimes have correlated only weakly (the present data), it would be difficult to extend findings from a study that focused primarily on the

dt_{ce} to studies in which the conclusions were drawn on the basis of a different measure. The variability in the relationship between the dt_{ce} and ILM_{area} is attributed to the fact that the dt_{ce} is considered a complex measure that generally reflects aspects of the decision after the motion signal has been generated (Ha et al., 2018), whereas the area measure generally reflects processes that lead up to the perception of motion.

Although the dt_{ce} indicates that an illusion has occurred, because the decision is based on the resulting motion, the dt_{ce} seems primarily related to postillusion processes. The strength of the illusion influences those decision processes by increasing or decreasing the resulting motion signal upon which the participant bases the response choice. It is interesting to note that the study in which the strongest relationship between ILM_{area} and the dt_{ce} was found was one in which the ILM decision was nested within a speeded choice reaction time task (Ha et al., 2018), which appears to have helped increase the correspondence between the strength of the illusion as measured by ILM_{area} and the dt_{ce} . This may have occurred because, when participants were encouraged to respond quickly during the cueing task, this attitude extended to the ILM trials, resulting in their decision times being more consistently influenced by the overall strength of the motion signal. In studies in which response times are not so strongly emphasized, such as the present one, individual variation with regard to other aspects associated with decision making may simply swamp this relationship. Regardless, the unstable pattern of the relationship between ILM_{area} and the dt_{ce} is consistent with the idea originally suggested in Han et al. (2016), that the dt_{ce} reflects decision-making postmotion perception rather than the processes that result in the illusory motion. In other words, ILM_{area} measures appear to reflect aspects up to the generation of the illusory motion, whereas the dt_{ce} appears to reflect processes subsequent to the generation of the motion percept, with the generally weak correlation between the measures reflecting how both either reflect (ILM_{area}) or are influenced by (dt_{ce}) the strength of the perceived motion. One interesting aspect of the decision time data is the ordering of the decision times to purely illusory motion, with PGM resulting in the fastest decisions, followed by the two attention-based illusions ($flashILM$ and $paintILM$, which did not differ), followed in turn by TAM. This pattern is consistent with the motion signal being generated earlier in PGM displays, being generated at a later point by a flash, and being generated even later by TAM displays. This ordering corresponds well with the notion that PGM is generated from early visual cortex, that flash-based illusions reflect the influence of the attentional system, presumably on the information that originates from early visual cortex, and TAM by the object system interpreting the bar as the box having changed shape, and therefore operating only after the presentation of the bar. Although this pattern is open to many alternative explanations (Popper, 1968), it affords no objection to the interpretations derived from the overall pattern of results.

Although our suggestion that there are three separate illusions may appear overly complex, we believe these illusions all reflect aspects of the normal workings of the visual system and of how real motion may be augmented due to the fundamental importance of detecting motion. For example, a general heightening of sensitivity in the vicinity of objects in our visual field would facilitate the detection of any object that emerges from behind an occluding object. Such emergence would require movement of the originally hidden object, so PGM could reflect the signaling of such motion. TAM, on the other hand, may reflect not only object tracking, as an object shifts from one location to another, but also changes in an object's posture. Shifts of limbs or body attitude would change the projected shape of an object, because of the associated movements. TAM might reflect how the object system works to enhance subtle changes in posture, movements that might serve to inform the viewer as to the intentions of the viewed object. Finally, $flashILM$ reflects the role of how attention, when captured to peripheral events, enhances signals from that location. Interestingly, $flashILM$ also seems to redistribute attention (Hamm & Klein, 2002) and to facilitate saccades away from the initial luminance flash (Crawford et al., 2006), effectively aiding fixation of where an initial attractor of attention has moved to rather than the location it was in when it originally captured attention. Such possibilities, although speculative, are presented here in order to illustrate how separate explanations for PGM, TAM, and $flashILM$ are not implausible fits to the bigger picture of the function of the visual processing system. Moreover, through the study of illusory motion, or even illusions in general, theoretical suggestions with respect to the normal functioning of the visual system are possible.

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References

- Brysbaert, M. (1990). A warning about millisecond timing in Turbo Pascal. *Behavior Research Methods, Instruments, & Computers*, 22, 344–345. <https://doi.org/10.3758/BF03209830>
- Christie, J. (2014). Illusory line motion is not caused by object-differentiating mechanisms or endogenous attention. *Quarterly Journal of Experimental Psychology*, 67, 2293–2300. <https://doi.org/10.1080/17470218.2014.918633>
- Christie, J., & Klein, R. M. (2005). Does attention cause illusory line motion? *Perception & Psychophysics*, 67, 1032–1043. <https://doi.org/10.3758/BF03193629>

- Corballis, P. M., Funnell, M. G., & Gazzaniga, M. S. (2002). An investigation of the line motion effect in a callosotomy patient. *Brain and Cognition*, 48, 327–332. <https://doi.org/10.1006/brcg.2001.1371>
- Crawford, T. J., Hamm, J. P., Kean, M., Schmechtig, A., Kumari, V., Anilkumar, A. P., & Ettinger, U. (2010). The perception of real and illusory motion in schizophrenia. *Neuropsychologia*, 48, 3121–3127. <https://doi.org/10.1016/j.neuropsychologia.2010.06.027>
- Crawford, T. J., Kean, M., Klein, R. M., & Hamm, J. P. (2006). The effects of illusory line motion on incongruent saccades: Implications for saccadic eye movements and visual attention. *Experimental Brain Research*, 173, 498–506. <https://doi.org/10.1007/s00221-006-0392-z>
- Downing, P. E., & Treisman, A. M. (1997). The line-motion illusion: Attention or impletion? *Journal of Experimental Psychology: Human Perception and Performance*, 23, 768–779.
- Faubert, J., & von Grünau, M. (1995). The influence of two spatially distinct primers and attribute priming on motion induction. *Vision Research*, 35, 3119–3130. [https://doi.org/10.1016/0042-6989\(95\)00061-4](https://doi.org/10.1016/0042-6989(95)00061-4)
- Ha, H. Y., Li, D., Patten, B., & Hamm, J. P. (2018). The relationship between flash based Illusory Line Motion and visual exogenous attention. *Canadian Journal of Experimental Psychology*, 72, 38–47. <https://doi.org/10.1037/cep0000122>
- Hamm, J. P. (2001). Object-oriented millisecond timers for the PC. *Behavior Research Methods, Instruments, & Computers*, 33, 532–539. <https://doi.org/10.3758/BF03195412>
- Hamm, J. P. (2017). A comparison of colour, shape, and flash induced illusory line motion. *Attention, Perception, & Psychophysics*, 79, 911–928. <https://doi.org/10.3758/s13414-016-1269-2>
- Hamm, J. P., Crawford, T. J., Nebl, H., Kean, M., Williams, S. C., & Ettinger, U. (2014). Neural correlates of illusory line motion. *PLoS ONE*, 9, e87595. <https://doi.org/10.1371/journal.pone.0087595>
- Hamm, J. P., & Klein, R. M. (2002). Does attention follow the motion in the “shooting line” illusion? *Perception & Psychophysics*, 64, 279–291. <https://doi.org/10.3758/BF03195792>
- Han, S., & Hamm, J. P. (2018). Flash induced forward and reverse illusory line motion in offset bars. *Attention, Perception, & Psychophysics*, 80, 951–970. <https://doi.org/10.3758/s13414-018-1482-2>
- Han, S., Zhu, Z., Corballis, M. C., & Hamm, J. P. (2016). Illusory line motion in onset and offset bars. *Attention, Perception, & Psychophysics*, 78, 2579–2611. <https://doi.org/10.3758/s13414-016-1170-z>
- Heathcote, A. (1988). Screen control and timing routines for the IBM microcomputer family using a high-level language. *Behavior Research Methods, Instruments, & Computers*, 20, 289–297. <https://doi.org/10.3758/BF03203845>
- Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993a). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research*, 33, 1219–1240. [https://doi.org/10.1016/0042-6989\(93\)90210-N](https://doi.org/10.1016/0042-6989(93)90210-N)
- Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993b). Visual attention revealed by an illusion of motion. *Neuroscience Research*, 18, 11–18.
- Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993c). Voluntary and stimulus-induced attention detected as motion sensation. *Perception*, 22, 517–526. <https://doi.org/10.1068/P220517>
- Hubbard, T. L., & Ruppel, S. E. (2011). Effects of temporal and spatial separation on velocity and strength of illusory line motion. *Attention, Perception, & Psychophysics*, 73, 1133–1146. <https://doi.org/10.3758/s13414-010-0081-7>
- Hubbard, T. L., & Ruppel, S. E. (2018). Does Allocation of attention influence relative velocity and strength of illusory line motion? *Frontiers in Psychology*, 9, 147. <https://doi.org/10.3389/fpsyg.2018.00147>
- Ipser, A., Karlinski, M., & Freeman, E. D. (2018). Correlation of individual differences in audiovisual asynchrony across stimuli and tasks: New constraints on temporal renormalization theory. *Journal of Experimental Psychology: Human Perception and Performance*, 44, 1283–1293. <https://doi.org/10.1037/xhp0000535>
- Jancke, D., Chavane, F., Naarman, S., & Girinvald, A. (2004). Imaging cortical correlates of illusion in early visual cortex. *Nature*, 428, 423–426.
- Jensen, A. R. (2006). Clocking the mind: Mental chronometry and individual differences. Amsterdam, The Netherlands: Elsevier.
- Kanizsa, G. (1951). Sulla polarizzazione del movimento gamma [On the polarization of Gamma motion]. *Archivio di Psicologia, Neurologia e Psichiatria*, 3, 224–267.
- Kanizsa, G. (1979). Organization in vision: Essays on Gestalt perception. New York, NY: Praeger.
- LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 371–379. <https://doi.org/10.1037/0096-1523.9.3.371>
- Masson, M. E. J. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior research methods*, 43, 679–690. <https://doi.org/10.3758/s13428-010-0049-5>
- Myors, B. (1999). Timing accuracy of PC programs running under DOS and Windows. *Behavior Research Methods, Instruments, & Computers*, 31, 322–328. <https://doi.org/10.3758/BF03207727>
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9, 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- Popper, K. R. (1968). The logic of scientific discovery (Rev. ed.). London, UK: Hutchinson.
- Raftery, A. E. (1995). Bayesian model selection in social research. *Sociological Methodology*, 25, 111–163. <https://doi.org/10.2307/271063>
- Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, 16, 225–237. <https://doi.org/10.3758/PBR.16.2.225>
- Searle, J. A., & Hamm, J. P. (2012). Individual differences in the mixture ratio of rotation and non-rotation trials during rotated mirror/normal letter discriminations. *Memory & Cognition*, 40, 594–613. <https://doi.org/10.3758/s13421-011-0172-2>
- Searle, J. A., & Hamm, J. P. (2016). Asymmetric response time functions during left-/right-facing discriminations of rotated objects: The short and the long of it. *Memory & Cognition*, 44, 124–142. <https://doi.org/10.3758/s13421-015-0540-4>
- Steinman, B. A., Steinman, S. B., & Lehmkuhle, S. (1995). Visual attention mechanisms show a center-surround organization. *Vision Research*, 35, 1859–1869. [https://doi.org/10.1016/0042-6989\(94\)00276-R](https://doi.org/10.1016/0042-6989(94)00276-R)
- Troscianko, T., & Low, I. (1985). A technique for presenting isoluminant stimuli using a microcomputer. *Spatial Vision*, 1, 197–202. <https://doi.org/10.1163/156856885X00198>
- Tse, P., Cavanagh, P., & Nakayama, K. (1998). The role of parsing in high-level motion processing. In T. Watanabe (Ed.), High-level motion processing: Computational, neurobiological, and psychophysical perspectives (pp. 249–266). Cambridge, MA: MIT Press.
- Tse, P. U. (2006). Neural correlates of transformational apparent motion. *NeuroImage*, 31, 766–773. <https://doi.org/10.1016/j.neuroimage.2005.12.029>
- von Grünau, M., Dube, S., & Kwas, M. (1996). Two contributions to motion induction: A preattentive effect and facilitation due to attentional capture. *Vision Research*, 36, 2447–2457.
- von Grünau, M., & Faubert, J. (1994). Intraattribute and interattribute motion induction. *Perception*, 23, 913–928. <https://doi.org/10.1068/p230913>