CrossMark

Flash-induced forward and reverse illusory line motion in offset bars

Sihang Han[1] · Jeff P. Hamm[1]

Abstract
Illusory line motion (ILM) refers to perception of motion in a bar that onsets or offsets all at once. When the bar onsets or offsets between two boxes after one of the boxes flashes, the bar appears to shoot out of the flashed box ($_{flash}$ILM). If the bar offsets during the flash, it appears to contract into the flashed box (reverse ILM; rILM). Onset bars do not show rILM. Moreover, rILM and $_{flash}$ILM are not correlated, indicating they are two different illusions. To date, rILM has only been studied using a 50-ms flash where the bar offsets 16.7 ms after flash onset. It is not clear if rILM is due to the 16.7-ms flash-bar-removal stimulus onset asynchrony (SOA) or due to the flash offsetting after the bar. The current studies explore these parameters to better understand the conditions that lead to rILM. The results suggest that $_{flash}$ILM is sensitive to the temporal interval between flash onset and bar offset, while rILM appears to arise when the flash offsets after the bar has been removed regardless of the temporal interval between flash onset and bar removal. These results are consistent with $_{flash}$ILM reflecting visual exogenous attention while rILM may reflect the low-level spreading of subthreshold activation radiating from the flashed box. The findings are incorporated into the recent work that suggests that the literature concerning ILM is possibly conflating a number of different illusions of line motion, including polarized gamma motion (PGM), transformational apparent motion (TAM), and exogenous attention induced motion ($_{flash}$ILM).

Keywords Attention · Motion: apparent · Visual perception

When a bar that joins two boxes is removed following the flash of one of the boxes, the bar appears to contract into the nonflashed box (Crawford et al., 2010; Han, Zhu, Corballis, & Hamm, 2016), with motion away from the flash. Illusory motion away from the flash ($_{flash}$ILM) also occurs if the bar suddenly appears between the boxes, where it appears to shoot out of the flashed box (Christie, 2014; Christie & Klein, 2005; Hamm, 2017; Han et al., 2016; Hikosaka, Miyauchi, & Shimojo, 1993c) (see Fig. 1a). The onset and offset illusions away from the flash are correlated at the participant level, meaning the size of a participant's onset illusion predicts the size of the participant's offset illusion, suggesting the two illusions arise for similar underlying reasons and require a common theoretical explanation (Han et al., 2016). An individual's onset illusion has also been shown to be correlated to their costs plus benefits from exogenous cuing (Ha, Li, Patten,

& Hamm, 2017), which suggests that onset $_{flash}$ILM is related to exogenous visual attention, and by extrapolation so is the offsets version of $_{flash}$ILM. Further supporting this conclusion is the fact that offset $_{flash}$ILM activates areas associated with motion and visual attention (Hamm et al., 2014), is reduced in a patient population known to have deficits in attention (Crawford et al., 2010), and that it can be generated by nonvisual cues of attention (Shimojo, Miyauchi, & Hikosaka, 1997). These findings are consistent with predictions drawn from the attentional gradient explanation for $_{flash}$ILM (Hikosaka, Miyauchi, & Shimojo, 1993a, 1993b, 1993c) and also support a common explanation for both the onset and offset $_{flash}$ILM (Han et al., 2016).

If, however, the bar is removed shortly after flash onset, the illusion reverses direction and the bar appears to contract into the flashed box (Hamm et al., 2014; Han et al., 2016). This illusion into the flashed box has been termed reverse ILM (rILM), and it does not appear to occur with onset bars nor is it correlated with $_{flash}$ILM (Han et al., 2016). These findings suggest that rILM is a different illusion requiring a separate explanation from $_{flash}$ILM. If separate explanations are required for $_{flash}$ILM and rILM, then the fact that rILM is hard

✉ Jeff P. Hamm
   j.hamm@auckland.ac.nz

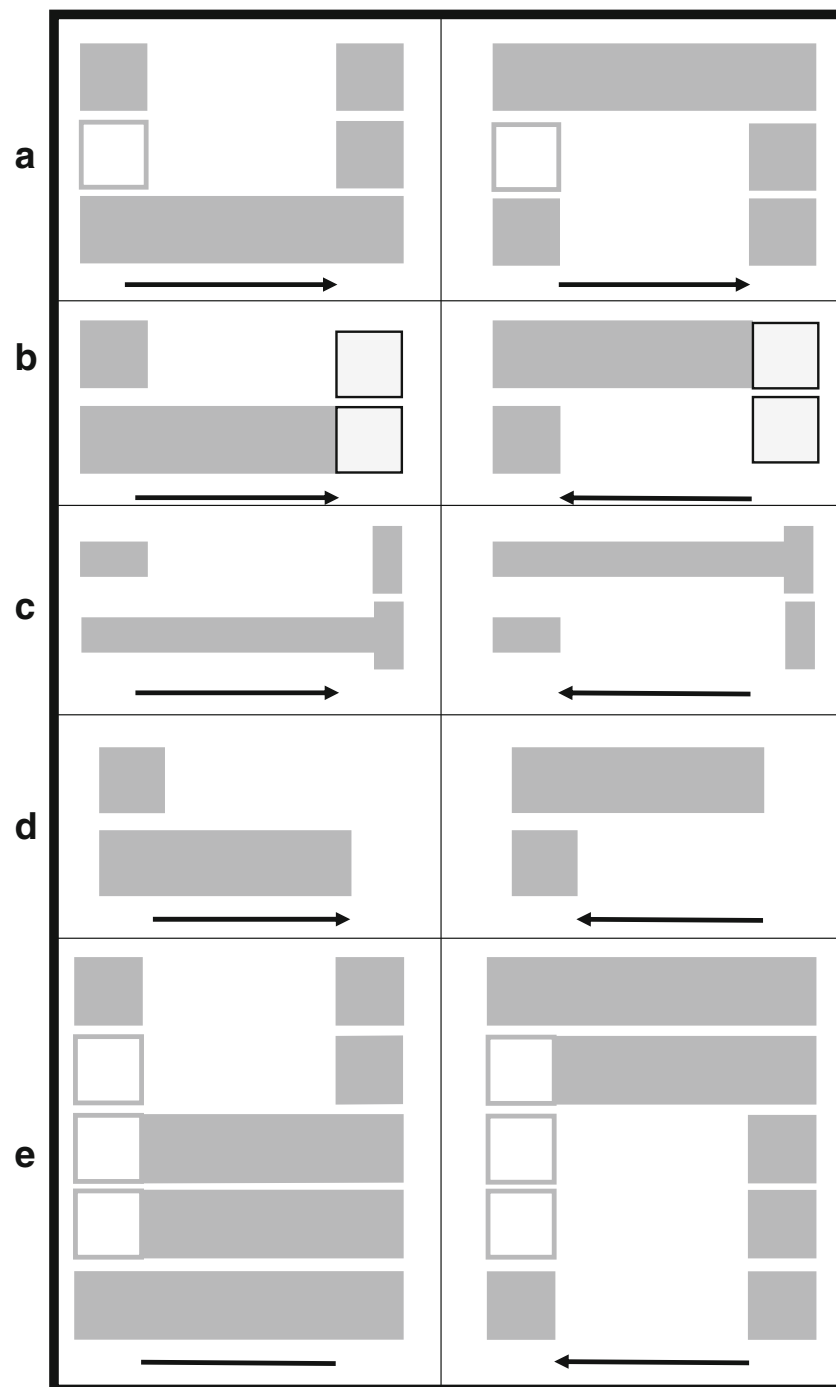[1] School of Psychology, The University of Auckland, Auckland, New Zealand

Springer

Fig. 1 Depicture of stimulus conditions that result in (**a**) flash-induced illusory line motin ($_{flash}$ILM) ; (**b**) colour-induced transformational apparent motion ($_{colour}$TAM); (**c**) shape-induced transformational apparent motion ($_{shape}$TAM); (**d**) polarized gamma motion (PGM) ; and (**e**) reverse illusory line motion following a flash (rILM). The left column shows onset line conditions and the right column shows offset line conditions. Arrows below each figure indicate the direction of the illusion, with no arrows indicating no illusion (onset lines have failed to show rILM). The initial display of each sequence may be of a long duration. The duration of the flash depicted in the $_{flash}$ILM conditions can vary, but is generally under 150 ms, and typically around 50 ms but can be shorter. In the rILM conditions, each flash segment represents 16.7 ms as rILM has so far only been tested with 50 ms flashes, with the onset/offset of the bar occurring 16.7 ms following flash onset

to reconcile under the attentional gradient account of $_{flash}$ILM is a moot point, though it furthers the argument for classifying $_{flash}$ILM and rILM as separate illusions. While the focus of the current studies is to investigate display parameters necessary

to generate rILM and $_{flash}$ILM—specifically, the flash duration, flash-bar SOA, and whether the real motion used to cancel the illusion should start earlier or end later in time as the real motion becomes slower—a brief discussion on the past

literature is necessary because it appears that quite subtle changes in the display conditions can result in phenomenologically similar illusions but for separate underlying reasons. In other words, the past literature refers to ILM as a unitary phenomenon despite employing a wide range of experimental protocols. Only recently has an attempt been made to test the assumption that all display configurations result in related illusory phenomenon, and this assumption has been found to be unsafe in a number of conditions (Hamm, 2017; Han et al., 2016). The following section will focus on the methodologies with respect to the literature on illusory line motion and will present the evidence that leads to the suggestion that not all studies investigating illusory line motion are studying the same phenomenon.

While onset and offset bars that are presented between two boxes following a flash result in illusory motion that can be explained by, and is predicted by, a gradient of visual attention, there are conditions that produce perceptually similar motion illusions, other than rILM, that cannot be explained by a gradient of attention. For example, if two differently coloured boxes are presented and are subsequently joined by a bar that matches in colour with one of the boxes (see Fig. 1b), the bar will appear to shoot out of the same-coloured box. This form of illusory line motion is referred to as transformational apparent motion (TAM; Tse, Cavanagh, & Nakayama, 1998), attribute priming (Faubert & von Grünau, 1995), or $_{colour}$ILM (Hamm, 2017; hereafter, this will be referred to as $_{colour}$TAM to emphasize that this illusion is unrelated to $_{flash}$ILM, as will be covered shortly). A similar attribute-based illusory line motion ($_{shape}$ILM, hereafter $_{shape}$TAM) occurs if the boxes are of different heights and the bar matches the height of one of the boxes (see Fig. 1c). Similar to $_{colour}$TAM, $_{shape}$TAM takes the form of illusory motion away from the matching box with onset bars (Corballis, Funnell, & Gazzaniga, 2002; Hamm, 2017; Tse, 2006) and towards the matching box for offset bars (Tse, 2006). However, while $_{colour}$TAM and $_{shape}$TAM are correlated, suggesting they arise for a common underlying reason, neither is correlated with $_{flash}$ILM (Hamm, 2017). Moreover, the TAM illusions activates motion and object regions of the brain (Tse, 2006) while $_{flash}$ILM activates motion areas and attentional networks (Hamm et al., 2014). With $_{flash}$ILM also empirically linked to the costs plus benefits of exogenous attentional cuing (Ha et al., 2017), and TAM forms of ILM ($_{colour}$TAM and $_{shape}$TAM) dissociated from $_{flash}$ILM on both behavioural (Hamm, 2017) and neurological (Hamm et al., 2014; Tse, 2006) grounds, it follows that these TAM-based forms of ILM do not challenge the attentional gradient explanation for $_{flash}$ILM but rather further the argument that there are multiple forms of ILM, each arising for different, separable, and nonmutually exclusive reasons.

Additionally, in the literature there are many studies that employ a display configuration where a single box is presented for an extended period of time and then the bar suddenly appears touching, or in close proximity, to it (see Fig.1d). This illusion was originally referred to as polarised gamma motion (PGM) when first reported (Kanizsa, 1951, 1979); but when it was rediscovered using displays where the single box would suddenly appear or disappear, it was named illusory line motion (Hikosaka et al., 1993a). The term *illusory line motion*, however, was also used in reference to studies employing the two box displays that produce $_{flash}$ILM (Hikosaka et al., 1993c) on the untested assumption that both displays were generating the same illusion. However, in PGM, onset bars appear to shoot out from the single box, but offset bars appears to shoot into the box (Schmidt & Klein, 1997; and noted in von Grünau & Faubert, 1994). While $_{flash}$ILM and rILM are not correlated with each other (e.g. meaning knowing if a participant shows a large $_{flash}$ILM does not indicate they will also show a large rILM; Han et al., 2016), it has not been determined whether or not PGM and reverse PGM are correlated, although this relationship has always been implied. The reversal of PGM's direction between onset and offset bars is unlike how both onset and offset $_{flash}$ILM manifest as motion away from the inducing flash (Han et al., 2016). PGM can be explained by the subthreshold spreading of activity away from the single box (Jancke, Chavane, Naarman, & Girinvald, 2004), as this would speed the detection of the near end of onset bars and sustain the activity of the near end after offset.

The motion in PGM and $_{colour}$TAM has also been suggested to be due to motion energy inherent to the physical characteristics of the display (Skottun, 2011). While this may be true, given that it has been empirically demonstrated that $_{colour}$TAM is unrelated to $_{flash}$ILM (Hamm, 2017), this leads to the conclusion that low-level motion energy inherent to the display is not the explanation for $_{flash}$ILM but that $_{flash}$ILM arises for a separate, or at least additional, reason. Again, if one constructs an explanation for onset bar $_{flash}$ILM along the lines of where the flash weights that end of the display in such a way that the onset of the bar now creates the low-level motion energy away from the flash, then the offset bars should reverse that motion energy, as with offset PGM. However, offset $_{flash}$ILM is not towards the flash. Furthermore, it should be mentioned, even though beyond the scope of the current investigation, that it has yet to be established if a participant's PGM and TAM ILM are or are not correlated. If they are, then that would suggest a single explanation would need to account for both. Currently, the object tracking account for TAM (Tse et al., 1998; Tse, 2006) and the motion energy account offered by Skottun (2011) appear to be adequate, and nonmutually exclusive, candidates. However, $_{colour}$TAM is known to originate from two locations, causing the motion in the bar to appear to collide in the middle (Faubert & von Grünau, 1995), because there is no change in the location of the centre of gravity in these displays, at least some preference lays with the object tracking account.

Moreover, $_{shape}$TAM is reduced if the bar height does not match the box height (Tse, 2006), and it is absent if there is a small separation (0.32°) between the box and the bar despite the low-level motion energy being the same as when the bar touches the boxes (Tse, 2006). Additionally, $_{colour}$TAM is reduced if the bar does not match the height of the coloured boxes, while $_{flash}$ILM is not (Hamm, 2017).

The critical point is that studies and analyses based upon PGM and TAM paradigms cannot be viewed as a test of the attentional gradient explanation for $_{flash}$ILM. While it is possible that in some configurations and display conditions both $_{flash}$ILM and PGM or TAM may be induced (Hamm, 2017), the general conflating of two, possibly three, illusions only serves to complicate the issue. For example, in Hikosaka et al.'s (1993a) Experiment 5, a $_{flash}$ILM type set-up is presented, but rather than brighten one of the boxes as the attentional cue, one of the boxes is removed. At short SOAs, this results in motion away from the disappearing box. As the SOA increases, motion eventually is reported away from the single remaining box. While this was originally interpreted as demonstrating attention initially being drawn to the disappearing box's location, and then shifting to the remaining visible box, it is also possible that this result reflects $_{flash}$ILM at the short SOAs and the emergence or dominance of PGM at the longer SOAs as attention fades at the originally cued location.

The literature is complicated by the use of the term ILM, regardless of whether the paradigm employed might induce PGM, TAM, or $_{flash}$ILM. It should be noted that while the terms PGM and TAM are used, in many studies using PGM displays in particular, the general term of ILM is used. While ILM unquestionably describes the perceptual phenomena (illusion of motion in a line/bar), it is unsafe to assume that the reason for the perceptual phenomenon in each of these situations is the same. A further complication arises in studies where a single box suddenly appears or disappears, as this method may result in setting up the display conditions that produce both PGM and $_{flash}$ILM in the same direction. Given that PGM appears to occur for as long as there is an inducing stimulus present, but $_{flash}$ILM is thought to be linked to the attentional gradient that rapidly decays over time, interpretation of such studies becomes even more complex. While PGM and TAM are not the focus of the current studies, it is critical to keep in mind that PGM, TAM, and $_{flash}$ILM may each arise for independent, and nonmutually exclusive, reasons and to set aside previous conclusions that extend beyond the illusion as investigated in the previous articles. Therefore, when evaluating theoretical statements aimed specifically at explaining $_{flash}$ILM, or indeed any of these illusions, a careful examination of a study's methodology must be undertaken and compared with the methodologies used in the previous literature. Where previous literature employs paradigms of a different nature to a given study's methodology, unless it has been established that the illusions generated by these two paradigms are related to each other (i.e. $_{colour}$TAM and $_{shape}$TAM; Hamm, 2017), then it should be assumed that different illusions of a similar perceptual nature are being generated.

The impact of subtle changes in methodology are exemplified by rILM and $_{flash}$ILM (Hamm et al., 2014). To reiterate the subtle differences that result in rILM and $_{flash}$ILM, when a bar is removed from between two boxes 16.7 ms after the onset of a 50-ms flash, the bar appears to contract into the flashed box (see Fig. 1e; Hamm et al., 2014; Han et al., 2016). However, if the bar is removed at the 50-ms point, so on the same frame that the flash offsets, then the bar appears to shoot away from the flash (see Fig. 1a; Hamm et al., 2014; Han et al., 2016). The illusion of motion towards the flash (rILM) may reflect an extension of the duration of the previously existing bar near the flash through creating increased amounts of subthreshold spreading of activity relative to near the nonflashed box (Jancke et al., 2004). However, such an explanation would predict an illusion away from the flash for onset bars appearing at 16.7 ms into the flash, and this does not appear to occur (Han et al., 2016). Therefore rILM cannot be explained by the attentional gradient unless one posits that attention acts to sustain an existing stimulus (Schmidt & Klein, 1997). However, that addition then fails to explain the more easily predicted offset $_{flash}$ILM away from the flash when the bar offsets at the 50-ms flash-bar SOA. Moreover, rILM is not correlated with $_{flash}$ILM (Han et al., 2016), and while one could argue that the magnitude of the attentional temporal extensions are unrelated to the magnitude of the attentional accelerations, to make such an argument is to concede that rILM arises for reasons separate from $_{flash}$ILM.

If rILM arises for reasons different from $_{flash}$ILM, then it is important to know what aspects of the display are critical to its production. To quantify the illusory motion, real motion can be used to cancel the illusion by drawing or removing the bar towards or away from the flashed box (Crawford et al., 2010; Ha et al., 2017; Hamm, 2017) while participants respond by indicting the direction they perceived the bar to be moving. Left responses are scored as −1 and right responses as +1, with the mean of these percept scores being plotted as a function of the real motion for the left and right flash conditions separately. With a right-side flash producing more leftward responses and a left-side flash producing more rightward responses, the area under the left flash response curve will be larger than the area under the right flash response curve. Therefore, the illusion is quantified by subtracting the area under the right flash curve from the area under the left flash curve to produce the measure ILM$_{area}$ (see Fig. 2). Due to the order of subtraction always being the area under the right flash response curve subtracted from area under the left flash response curve, ILM$_{area}$ has a positive value for illusions away from the flash (Ha et al., 2017; Hamm, 2017; Han et al., 2016) and a negative value for illusions towards the flash (rILM; Han et al., 2016).
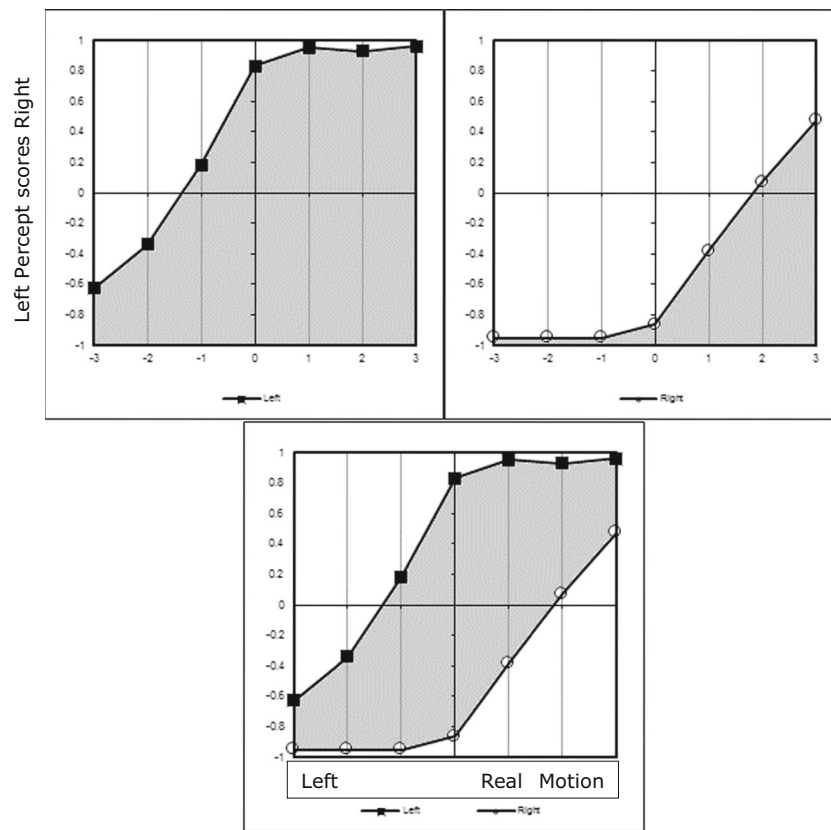
Fig. 2 The area under the (**a**) left and (**b**) right percept score curves are shown by the shaded regions and are calculated as the sum of a series of trapezoids. The area between the two curves (**c**) is calculated by subtracting the area under the right flash condition (**b**) from the area under the left flash condition (**a**). This quantity is referred to as ILM_{area}.

If the direction of the illusion were to reverse such that a left flash results in an increased perception of leftward motion and a right flash results in an increased perception of rightward motion, then the data shown in **a** and **b** would swap resulting in a negative value due to the subtraction always being performed as left flash area minus right flash area

Cancelation of the illusory motion using real motion has also been used to measure PGM (Steinman, Steinman, & Lehmkuhle, 1995) and TAM (Hamm, 2017) illusions, making this a useful paradigm to compare between illusion types. Note, Steinman et al. (1995) employed a sudden onset of a single box and so may have evoked both PGM and $_{flash}ILM$. When discussing comparisons between the magnitude of rILM and $_{flash}ILM$, it should be remembered that it is the absolute value of ILM_{area} that reflects the size of the illusion, meaning an area of −4 for rILM indicates a larger reverse illusion than a value of +3 for $_{flash}ILM$. Use of ILM_{area} has shown that TAM and $_{flash}ILM$ summate, and so if PGM is a form of TAM, or even if it is a separate illusion again, there is no evidence to suggest this does not also happen with PGM and $_{flash}ILM$, or PGM and TAM.

Finally, due to the theoretical importance given to a finding of no correlation between two forms of illusory line motion, along with the traditional evaluation of the accuracy of the null-hypothesis' prediction based upon a test of significance, correlations are evaluated with a Bayesian pH0|D value. The pH0|D value reflects the probability of the null relative to the alternative given the data (Masson, 2011) rather than the probability of the data if one assumes the null (the p value from standard null-hypothesis significance testing). As pH0|D approaches zero, the null becomes more improbable, and as pH0|D approaches one, the null becomes more probable. A value of 0.5 means the null and the alternative are equally probable. Put another way, this means that the data in question are equally supportive of both the null and the alternative. Also, pH0|D is not described as being significant or nonsignificant, but rather descriptions for pH0|D are based upon the recommendations given by Raftery (1995), with the addition of a range to be interpreted as indicative of an equivocal finding (Ha et al., 2017). In short, the standard p value is an assessment of the accuracy of the prediction derived from the null hypothesis, and so rational evaluation of theory is based upon an evaluation of its accuracy; effectively, we reject the null because it has been shown to make inaccurate predictions. However, this approach does not allow one to accept the null simply because it has not been rejected. In contrast, pH0|D is an assessment of preference for the null or the alternative once the data have been obtained, and so this approach allows one to evaluate the weight of evidence as being in favour of the null. The two probability values of p and

pH0|D should not be viewed as competing methods of evaluation but rather as complementary.

In order to present real motion, the bar must be drawn over time on successive screen refreshes. With the flash duration of 50 ms (three screen-refresh cycles), rILM has been shown to occur when the bar is removed all at once 16.7 ms (one screen) after flash onset (Hamm et al., 2014; Han et al., 2016). If the bar is removed on the same screen that the flash ends (50 ms after flash onset, or after three full screens, so it is removed at the start of the fourth screen), then motion away from the flash occurs, producing the offset-bar version of flashILM (Crawford et al., 2010; Hamm et al., 2014; Han et al., 2016). The slowest real motion in these studies removes a quarter of the bar per screen refresh, with medium speed removing a third of the bar per screen refresh, and fast motion being to remove the bar in halves over two screens. If the flashILM at 50 ms is a result of a gradient of exogenous attention that has built up since the onset of the flash, then starting motion only 16.7 ms post flash means slower real motion results in the presentation of parts of the bar over the time period the gradient is presumed to be growing and producing flashILM away from the flashed box. If rILM arises for reasons other than the attentional gradient, then this means both the processes responsible for flashILM and rILM may be active, with the end results the two illusions may interfere due to their opposite directions. The real motion can, however, be anchored such that the real motion is always completed at 16.7 ms into the flash rather than beginning at 16.7 ms into the flash. In this case, the slower motion begins increasingly earlier in time rather than finishing later in time. Starting the real motion earlier in time avoids the proposed cause of flashILM because the gradient of attention would build only after the real motion has completed.

Similarly, when the real motion is presented after the flash, unfolding the real motion over time, such that slower speeds finish later in time, presents the real motion along the established attentional gradient that should not fade substantially over the period of motion. However, beginning the slower motion earlier in time would mean the motion begins when the gradient is weak or nonexisting. Moreover, slower motion could overlap bar removal with aspects of the display that result in rILM unless rILM is due to the fact the flash does not offset until after the bar is removed. Therefore, trials in which the real motion was anchored to begin at either 16.7 ms or 50 ms post flash onset were mixed with trials where the real motion was anchored to complete at either 16.7 ms or 50 ms post flash onset in order to investigate motion perception over the time periods known to result in rILM and flashILM. In Han et al. (2016), where rILM and flashILM were shown to be unrelated, rILM was measured using bar removals where slower motion began earlier in time while flashILM was measured using bar removals where slower motion ended later in time. While these two conditions are the least likely to show overlap between rILM and flashILM if they are separate

illusions, the difference in the methodology of the temporal direction of how slower motion is presented with respect to the flash anchor point is undesirable. Moreover, the above hypotheses concerning how rILM and flashILM could both be activated should the bar motion occur over the period of the flash between 16.7 ms and 50 ms remains untested. Examination of motion perception under these conditions will provide further information to consider when attempting to provide explanations for the causes of these two separate illusions. This was the basis for Experiment 1.

Experiment 1

Method

Participants

Of the 25 participants who volunteered for this study, one failed to complete the experiment, leaving data from 24 participants for analysis (12 males, 12 females, mean age = 20.54 years, SD = 3.39, range: 17–30). Participants were recruited from the University of Auckland student body. All participants reported having normal or corrected-to-normal vision. Nineteen were right-handed, three were left-handed and two were ambidextrous, as determined by the Edinburgh Inventory (Oldfield, 1971). All participants were naïve to the purpose and predictions of the study. The study was approved by the University of Auckland Human Participants Ethics Committee. All participants provided informed written consent prior to participation.

Apparatus

The experiment program was written in Borland Pascal 7.0 and ran on a desktop Pentium 3, 500 MHz processor, personal computer with an S3 4 MB internal graphics card, 128 MB RAM running Windows 98, and rebooted in MS DOS mode for accurate millisecond timing (Myors, 1999). Stimuli were displayed on a 17-in. Philips Brilliance 17A monitor, running at 60 Hz. The screen resolution was 640 × 480 pixels, with 64 levels of grey. Luminance was measured five times for each RGB setting used with a Konica Minolta LS-110 luminance meter. The millisecond timing routines were based upon Hamm (2001), and the synchronisation of the timing with stimulus presentation was based upon Heathcote (1988). Left and right responses were made on the < and > keys of the keyboard, respectively.

Stimuli

The average of five luminance readings with the lighting on as per the experimental conditions are reported. The fixation

cross spanned $0.5° \times 0.5°$ and was drawn in black (3.89 cm/m^2) in the centre of the screen, with a background set to a neutral grey (34.05°). Two grey boxes ($1.9° \times 1.9°$, 57.96 cm/m^2) were positioned with their centres $1.2°$ above and $4.7°$ to the left and right of the centre of the fixation. The grey bar (57.96 cm/m^2) that joined the boxes spanned $7.5° \times 1.5°$ and was centre aligned with the boxes. When a box flashed, the luminance increased to 92.60 cd/m^2.

Design

The experimental design included four factors, namely the 3 cue locations (left, right, and none) × 7 levels of real motion (slow left, medium left, fast left, no real motion, fast right, medium right, and slow right, coded as −3 to +3, respectively) × 2 flash-bar motion relationships (bar motion anchor point during or after the flash) × 2 temporal directions with respect to slower motion (begins earlier and ends later), resulting in 84 experimental conditions. There were 10 repetitions of each condition, resulting in 840 trials per participant.

For statistical analysis, the illusion is indexed as the area between the percept scores following left and right cues (ILM$_{area}$; see Fig. 2). In the subsequent statistical analysis, the design is considered as having two factors, namely 2 levels of flash-bar motion relationships (bar motion anchor point during or after the flash) × 2 temporal directions with respect to slower motion (begins earlier and ends later) resulting in 4 conditions.

The same statistical design occurs for the decision-time measure, referred to as the decision-time congruency effect (dt$_{ce}$), as it has been previously shown that when the real motion and illusory motion are in the same direction, decision times are faster than when the illusory motion and real motion are in opposite directions (Ha et al., 2017; Hamm, 2017; Han et al., 2016). The dt$_{ce}$ is calculated by first averaging the decision times for all conditions involving rightward real motion (Motion 1, 2, 3) following a left cue, with all conditions involving leftward real motion (Motion −1, −2, −3) following a right cue. Second, the average decision time for all conditions involving rightward real motion following a right cue and all conditions involving leftward real motion following a left cue is calculated. Third, the dt$_{ce}$ is calculated as the difference between these values when subtracting the latter from the former. Similar to ILM$_{area}$, the dt$_{ce}$ results in a negative value for reverse illusions as the order of subtraction results in subtracting the slower incompatible conditions from the faster compatible conditions.

Procedure

The experiment was conducted in a well-lit room and required 45.75 minutes on average for the participants to complete. The participants sat with their heads resting on a chin rest positioned so their eyes were 57 cm from the monitor. The 840 trials were presented in a random order, and participants were able to take a self-timed break every 210 trials. Upon pressing a key to continue, a 2,000-ms delay was included before the next trial began.

Participants were verbally instructed to maintain fixation on the fixation cross at all times, to ignore any flashes, and to indicate the direction of perceived line motion by pressing the < and > keys for leftward and rightward motion, respectively. Participants were requested to make their decisions quickly, but not so fast as to make motor errors. Decision times were recorded from the removal of the first bar segment until a key press was detected. If participants did not know which way the bar moved, they were asked to guess. They were also instructed to distribute guesses between left and right rather than choose a default response when unsure.

A trial began with a 500-ms fixation display including the two boxes. Following this period, the left, right, or neither box brightened for 50 ms (three frames, 16.7 ms each frame) before returning to its starting luminance. The bar was removed over successive screen refreshes in quarters, thirds, halves, or all at once for slow, medium, fast, or no motion and coded from 3 down to 0, respectively. The motion was either leftward or rightward, with leftward motion coded as negative values, so −3 indicates slow leftward real motion. If no key was pressed after 4,000 ms, the trial terminated and was discarded from analysis without replacement. Whether a trial terminated with a response, or after a 4,000-ms period, the display was removed and there was a 1,000-ms intertrial interval before the beginning of the next trial. These instructions were also presented on the screen at the beginning of the experiment.

The timing of the bar removal was anchored either during the flash (16.7 ms, or one screen refresh after the flash onset) or after the flash on the same frame that the flash ended. These time periods will be referred to as during and after the flash. In addition, the anchoring was such that either the bar removal completed at the anchor point, which entails the slower real motion removing the bar beginning earlier in time, or the bar removal began on the anchor point, which entails completing the slower real motion later in time. This results in the four conditions of the statistical design: slower motion begins earlier and ends during the flash, slower motion ends later and begins during the flash, slower begins earlier and ends after the flash, and, finally, slower motion ends later and begins after the flash. Figure 3 illustrates two of these conditions at the slowest level of real motion, specifically, slow left motion beginning earlier and ending during the flash (left column) and slow left motion ending later when beginning after the flash (right column). Figure 4 depicts the temporal arrangements of the flash and motion conditions.

Results

In keeping with previous studies (Ha et al., 2017; Hamm, 2017; Han et al., 2016), of the 20,160 total number of trials
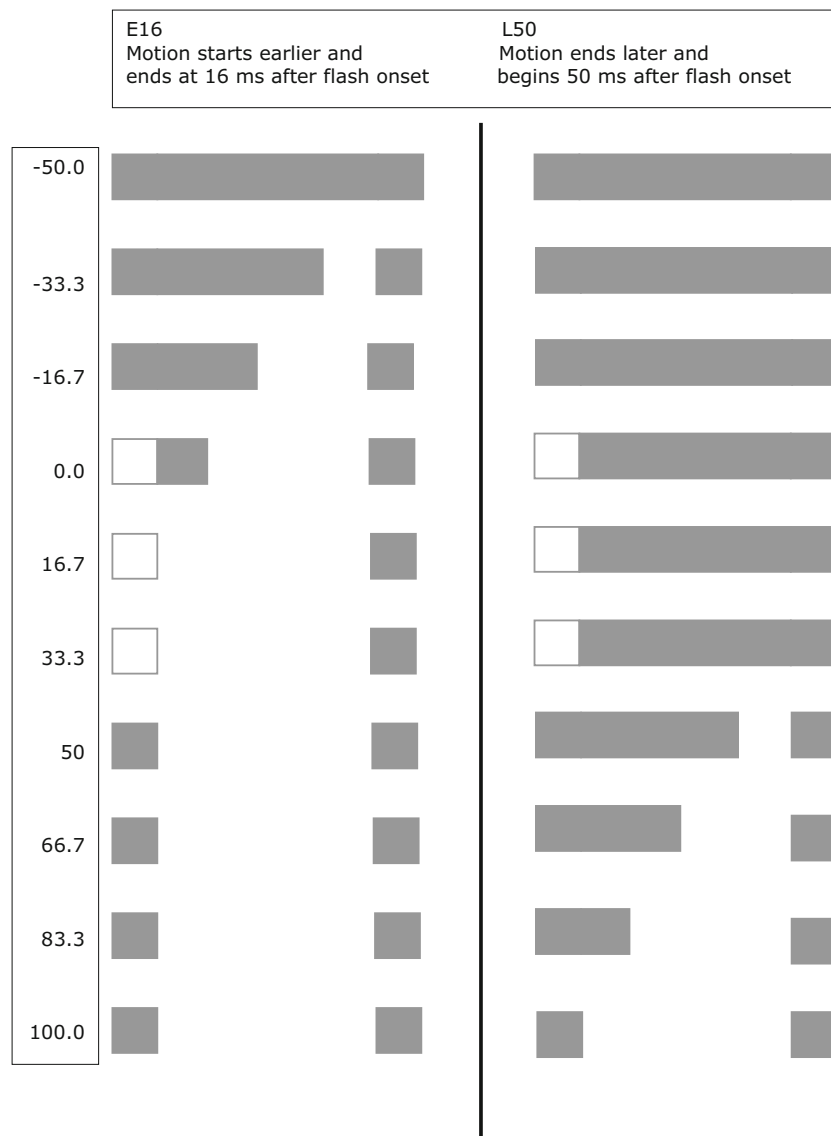
Fig. 3 Diagram showing slow motion to the left ending at 16.7 ms after flash onset (E16; left column) or slow motion to the left beginning at 50 ms after flash onset (L50; right column)

run, trials were dropped from the analysis if they had a decision time less than 200 ms (anticipations, 235; 1.17%), a decision time greater than 2,000 (distractions, 113; 0.56%), or if either an invalid key was pressed or no response was made by 4,000 ms (invalid response, 237; 1.18%), leaving 19,575 of the trials (97.10%) for analysis.

Percept scores

Percept scores were calculated by scoring a left response as −1 and a right response as +1 and averaging these scores. This is a simple linear transformation of scoring the data in terms of percentage of rightward responses, but it has the benefit of negative values indicating a majority of the responses are leftward while positive values indicate rightward, and a score of

zero indicates an equal distribution of responses between left and right.

The mean percept scores as a function of flash location and real motion for each of the flash–bar relationships (anchored 16.7 ms after flash onset with slower motion beginning earlier, E16; anchored 50 ms after flash onset with slower motion beginning earlier, E50; anchored 16.7 ms after flash onset with slower motion ending later, L16; and anchored 50 ms after flash onset with slower motion ending later, L50) can be seen in Fig. 5a–d. The measure ILM_{area} was calculated from each participant's data for statistical analysis. Single-sample t tests confirmed that ILM_{area} was non-zero for all conditions, $t(23) =$ −9.86, 14.71, −3.48, 11.96, all ps < .002, all pH0|D < 0.03, strong evidence against the null hypothesis ($M = −2.40$, 2.68, −0.78, and 3.36, for E16, E50, L16, and L50, respectively). The negative ILM_{area} values confirmed rILM in the E16 and
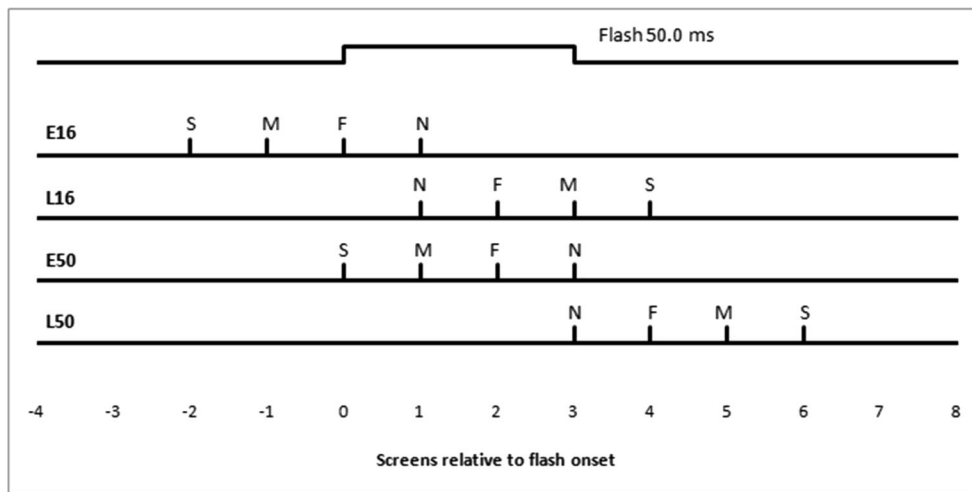
Fig. 4 Depiction of the temporal characteristics of the display employed in Experiment 1 in terms of 16.7-ms screen-refresh cycles relative to the flash onset at zero. Top line indicates the time period over which the flash (left or right) was presented. The lower four time lines indicate the E16, L16, E50, and L50 conditions, respectively. Points on the bar time lines indicate frames where a bar segment could be removed. During the E16 and E50 conditions, bar removal was always completed at point N, and removal began on the S, M, F, or N frame for slow, medium, fast, and no real motion trials, respectively, for both left and right real motion directions. On the L16 and L50 conditions, bar removal always began on the frame indicated by N and was completed at the N, F, M, or S frame for no motion, fast, medium, or slow real motion, respectively, for both left and right real motion directions
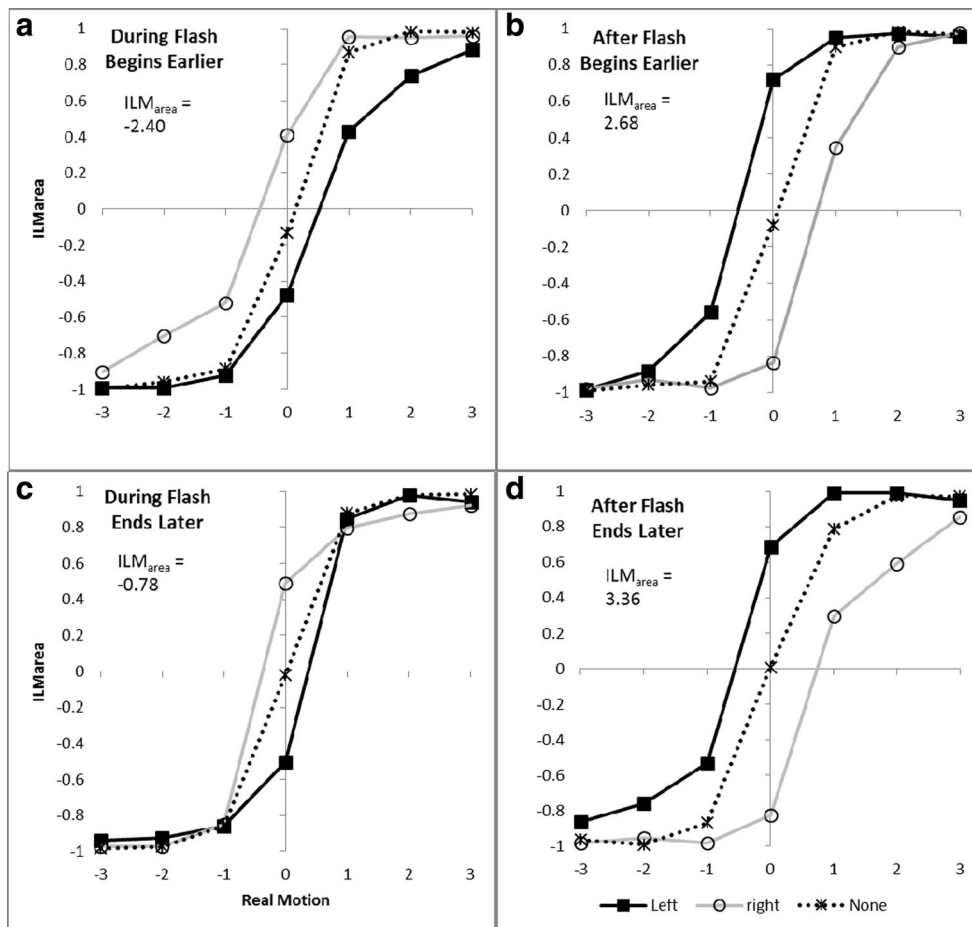

Fig. 5 Percept scores as a function of real motion for left flash (black lines filled squares), right flash (grey lines open circles), and no flash (dashed lines) for when the line removal (**a**) completes during the flash (**b**) completes after the flash, (**c**) begins during the flash, and (**d**) begins after the flash

L16 conditions and the positive ILM_{area} values confirmed $_{flash}ILM$ in the E50 and L50 conditions. ILM_{area}, ignoring the sign, was larger in the E16 condition compared with the L16, $t(23) = 6.48$, $p < .001$, pH0|D < 0.01, very strong evidence against the null hypothesis, while the L50 was larger than the E50, $t(23) = 3.52$, $p = .001$; pH0|D < 0.03, strong evidence against the null hypothesis.

Following the standard procedure of dropping any data pairs with a Cook's D that suggested it was an outlier (Ha et al., 2017; Hamm, 2017; Han et al., 2016), (criterion = 4/n = 0.167), ILM_{area} was correlated between E16 and L16, $r(20)$ = .4435, $p = .039$, pH0|D = 0.2966, weak evidence against the null hypothesis, two outliers. ILM_{area} was also correlated between E50 and L50, $r(21) = .8520$, $p < .001$, pH0|D < 0.001, very strong evidence against the null hypothesis, one outlier. The scatter plots may be seen in Fig. 6a. Fischer's z transformation indicates the relationship was stronger between E50 and L50 than E16 and L16 ($z = 2.46$, $p = .01$). ILM_{area} were averaged together over conditions where slower motion started earlier or it ended later, and the resulting $rILM_{area}$ values for during the flash were not related to the ILM_{area}
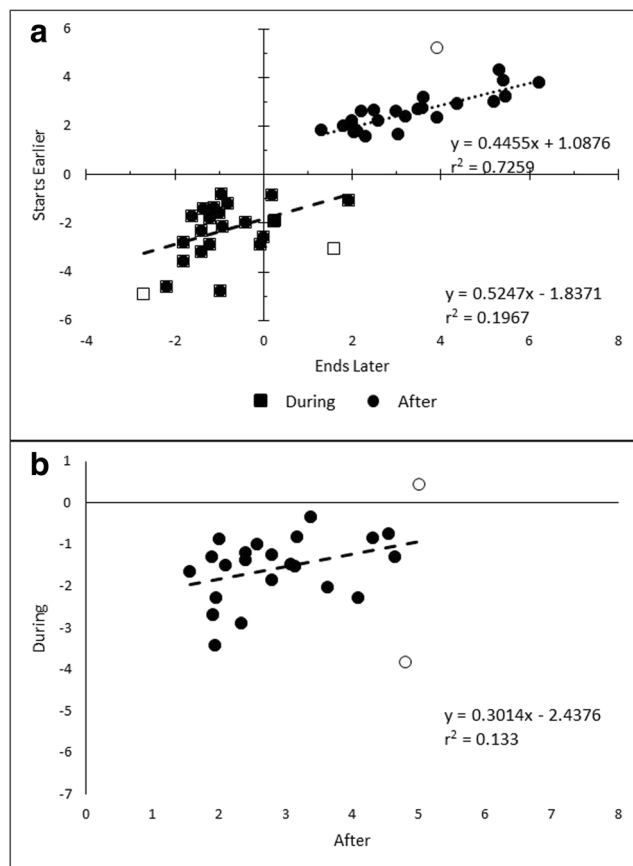

Fig. 6 Correlations between individual participant's ILM_{area} when slower real motion starts earlier in time and when slower real motion ends later in time when the motion is anchored during the flash (squares) and after the flash (circles). Open symbols indicate outlier data points based upon Cook's D

values for after the flash (see Fig. 5b), $r(20) = .3647$, $p = .095$, pH0|D = 0.4939, equivocal evidence, two outliers. While the pH0|D indicates the data are equally supportive of the null and experimental hypotheses, the potential correlation is in the wrong direction to suggest a common explanation for rILM and $_{flash}ILM$, but it may reflect either rILM or $_{flash}ILM$ is occurring in both.

Due to the equivocal finding, the data were explored further. First, the E16 and L50 conditions were compared as these are the conditions least likely to be a mixture of rILM and $_{flash}ILM$. The remaining two conditions, L16 and E50, were also tested for a correlation as these present real motion over common time points of the display. The E16 and L50 conditions were found to be unrelated, $r(20) = -.1341$, $p = .55$, pH0|D = 0.7935, positive evidence in support of the null hypothesis, replicating the lack of a relationship between rILM and $_{flash}ILM$ reported in Han et al. (2016) in these conditions, while the L16 and E50 were found to be correlated, $r(19)$ = .7897, $p < .001$, pH0|D < 0.001, very strong evidence against the null. The scatter plots may be seen in Fig. 7a–b.

The E16 and L50 conditions were taken as estimates of uncontaminated rILM and $_{flash}ILM$, respectively. The uncontaminated $rILM_{area}$ and $_{flash}ILM_{area}$ were then tested in a stepwise regression as predictors of the hypothesized combination, requiring $p < .05$ for entry and $p > 0.1$ for removal. When the stepwise regression was used to predict ILM_{area} from the E50 condition, only $_{flash}ILM_{area}$ was entered into the model $y = 0.278$ $_{flash}ILM_{area} + 0.529$, $r(21) = .732$, $p < .001$, pH0|D < 0.001, very strong evidence against the null, with no indication that the $rILM_{area}$ was a predictor, $r(21)$ = .073, $p = .741$, pH0|D = 0.8185, positive evidence in favour of the null. In contrast, both $rILM_{area}$ and $_{flash}ILM_{area}$ were entered when predicting the L16 condition ($y = 0.169$ $_{flash}ILM_{area} + 0.298$ $rILM_{area} - 0.292$), $r(21) = .669$, $p < .001$, pH0|D = 0.0190, strong evidence against the null. Therefore, while the L16 condition appears to reflect a combination of rILM and $_{flash}ILM$, the E50 condition seems to be generally reflective of only $_{flash}ILM$.

Decision times

The mean decision times may be seen in Fig. 8a–d. The decision-time congruency effect (dt_{ce}) was significantly different from zero in all conditions, $t(23) = -8.28$, 4.34, 2.40, and 10.18, $p < .001$, < .001, = .025, and < .001, all pH0|D < 0.26, weak evidence against the null hypothesis, although 3 of the 4 are very strong evidence against the null ($M = -80$, 27, 12, and 108, for the E16, E50, L16, and L50 conditions, respectively).

The point of subjective equality (PSE) was found by least squares fitting of the group mean percept scores to the log linear function scaled to the range -1 to $+1$; $2(e^{-ax + b}) - 1$ (Ha et al., 2017; Hamm, 2017; Han et al., 2016). The group mean decision times were then plotted as a function of
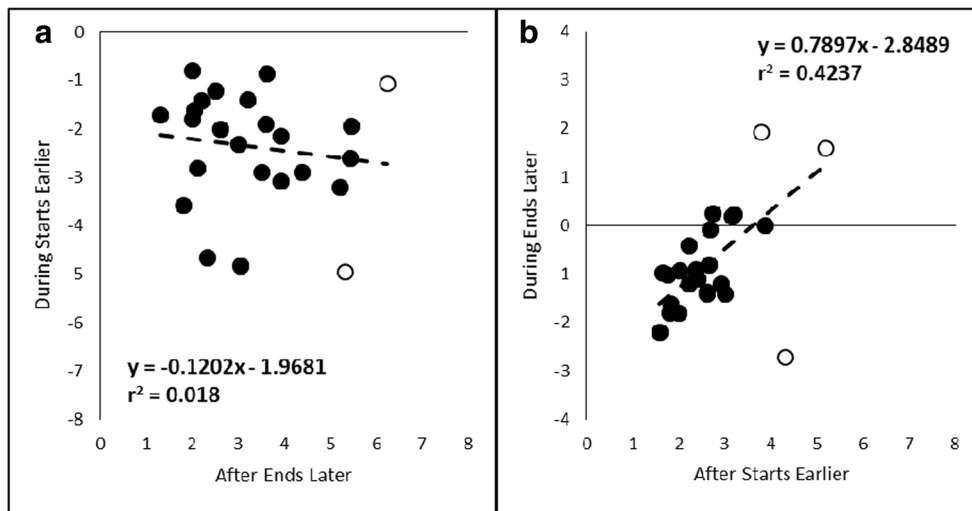
Fig. 7 Correlations in the percept scores between (**a**) real motion that starts after the flash when slower motion ends later in time and real motion that ends during the flash when slower motion starts earlier in time, and (**b**) real motion that ends after the flash when slower motion starts earlier in time and real motion that starts during the flash when slower motion ends later in time

distance from the PSE and were found to be described by an exponential decay function (see Fig. 9a–d) with a minimum of 48% of the variance explained, after discarding data points with excessive Cook's D values.
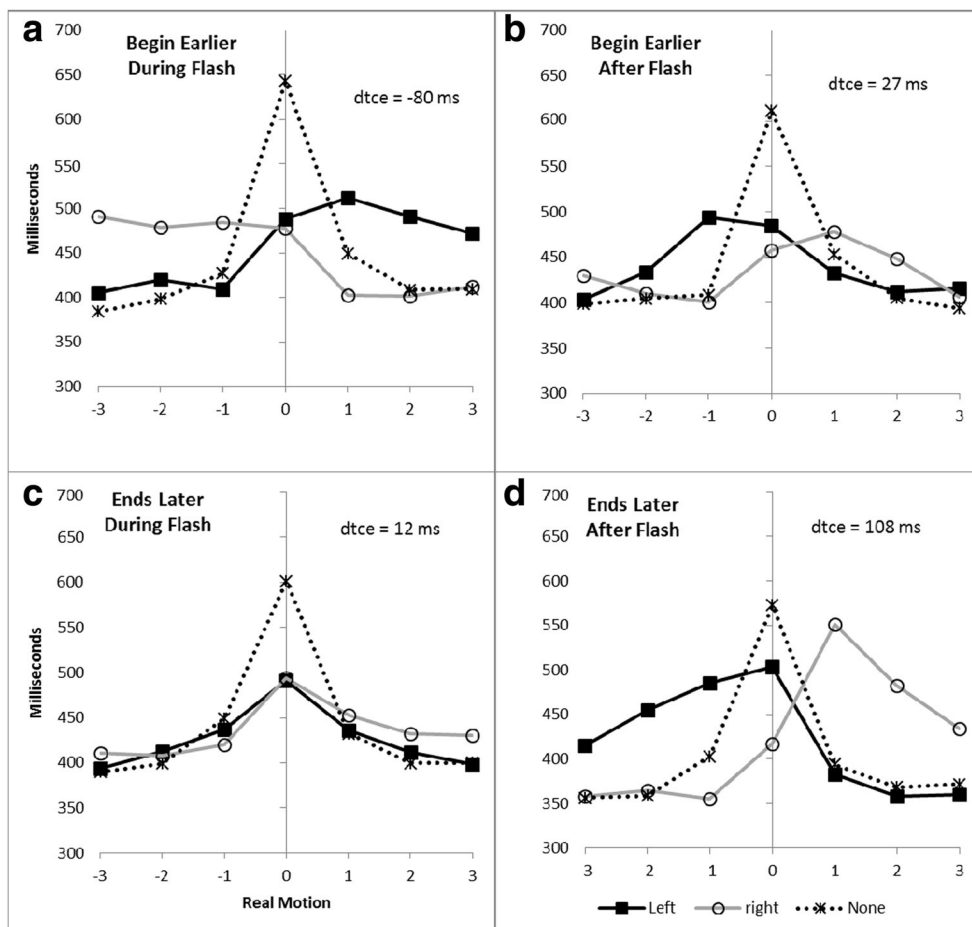

Fig. 8 Group mean decision times as a function of real motion speed following a left flash (black lines filled squares), right flash (grey lines open circles), and no flash (dashed lines) when the line removal (**a**) completes during the flash, (**b**) completes after the flash, (**c**) begins during the flash, and (**d**) begins after the flash
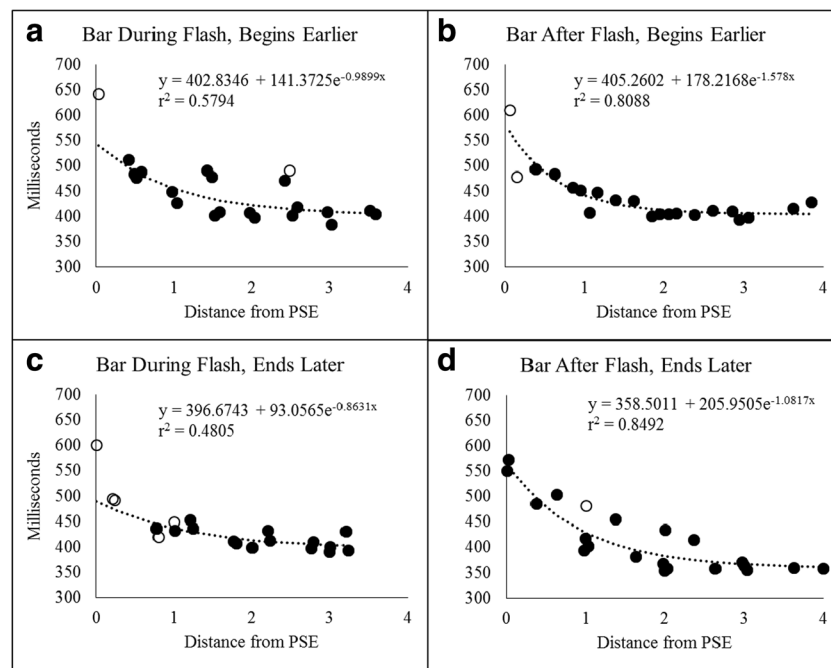
Fig. 9 Group mean decision times plotted as a distance decay function from the point of subjective equality for conditions where slower real motion begins earlier in time and is completed (**a**) during the flash and (**b**) after the flash, and conditions where slower real motion ends later in time and begins (**c**) during the flash and (**d**) after the flash

Discussion

All conditions produced illusory motion in the offset bars, with the conditions where the bar removal was anchored to a point during the flash showing rILM (illusory motion toward the flash) and conditions where the bar removal was anchored to the point after the flash showing $_{flash}$ILM (illusory motion away from the flash). ILM$_{area}$ from the $_{flash}$ILM conditions were correlated, indicating that $_{flash}$ILM was measured both with motion where slower motion began earlier and where slower motion ended later, although it was larger when the real motion ended later. It was found that rILM was larger when the bar was removed with slower motion starting earlier compared with when it was removed with slower motion ending later. The ILM$_{area}$ measures were correlated for both rILM versions, suggesting that rILM was being measured both when slower motion ended earlier and when slower motion ended later when the bar removal was anchored to be during the flash. In contrast, rILM$_{area}$ when the slower motion began earlier and was completed at 16.7 ms into the flash (E16) was unrelated to ILM$_{area}$ from the $_{flash}$ILM condition where motion ended later (L50), as previously shown (Han et al., 2016). However, when the bar removal began during the flash and slower motion ended later (L16), ILM$_{area}$ from this condition was also correlated with ILM$_{area}$ from the $_{flash}$ILM conditions, where the bar motion was anchored after the flash. These findings suggest that when bar removal began at 16.7 ms into the flash and slower motion ended later in time, both rILM and

$_{flash}$ILM were contributing to the motion percept, as confirmed by the stepwise regression which included both rILM and $_{flash}$ILM as predictors of rILM$_{area}$ from the L16 condition.

Three conditions showed a decision-time congruency effect (dt$_{ce}$) with the same sign as ILM$_{area}$, indicating faster decision times when the illusion and real motion were in the same direction. Only the condition where the bar removal was anchored to the 16-ms point during the flash and slower motion ended later (L16) showed the reverse. Effectively, the dt$_{ce}$ was consistent with $_{flash}$ILM (positive mean), while the percept scores were suggestive of rILM (negative mean). This conflict in findings is consistent with the suggestion based upon the stepwise correlation analysis that this condition may be reflecting both rILM and $_{flash}$ILM.

In all conditions, the decision times slowed as the condition approached the point of subjective equality and was described as an exponential decay function as has been previously shown (Ha et al., 2017; Hamm, 2017; Han et al., 2016). This pattern indicates that the real motion and the illusion, in both $_{flash}$ILM and rILM conditions, are cancelling and reducing the perceived motion (Crawford et al., 2010; Ha et al., 2017; Hamm, 2017; Han et al., 2016) as being closer to the response boundary (Cartwright, 1941), which in a nonbiased observer would be the perception of no motion. This interpretation is consistent with the finding that when a third response option of "no motion" is included, this option is chosen with increasing frequency as the condition approaches the PSE (Han et al., 2016). This conclusion will be further explored in the discussion of Experiment 2.

The main objective of Experiment 1 was to determine the best technique by which to independently measure rILM and flashILM. Based upon the current findings, rILM is best measured when the real motion is anchored to 16.7 ms post flash onset and slower motion bar removals begin earlier in time (E16). Although flashILM is maximized when bar removal begins at the 50 ms post flash onset time and slower motion ends later (L50), flashILM is also observable without contamination with rILM when slower motion starts earlier as well (E50). Therefore, in order to maximize rILM, and to maintain as much similarity between experimental conditions, rILM and flashILM will be examined using slower motion that starts earlier in both cases in Experiment 2.

In summary, the findings suggest that if the bar removal is anchored to the 50-ms point after the flash, then flashILM is produced and can be measured by bars that begin removal earlier or end removal later. In addition, rILM occurs if the bar is removed and anchored to a point 16.7 ms after flash onset but is best measured by bars that are removed starting earlier in time, as removing the bar such that slower motion ends later in time appears to also involve flashILM. Finally, rILM and flashILM appear to reflect two different illusory motions, as they are not correlated to each other.

The finding that starting the bar removal at 16.7 ms into the flash and using slower motion that ends later in time results in both rILM and flashILM illusions is consistent with the notion that the slower bar removals are now extending into a time period where the attentional gradient is growing and so produce flashILM. Consistent with this interpretation is the fact that ILM$_{area}$ is smaller when the slower real motion starts earlier in time and completes at 50 ms post flash onset because the bar removal would begin at a time when the gradient is not fully established, and therefore at a time when flashILM would be weaker or nonexistent. Furthermore, presenting slower motion over increasing time after the flash allows the gradient to continue to grow, resulting in larger flashILM. In short, the temporal dynamics involved in the presentation of the real motion and the presumed temporal dynamics of the underlying exogenous attentional gradient are both important factors to be considered and explored in future studies. While some studies have shown that illusory motion will reduce at longer flash-bar SOAs (Hikosaka et al., 1993a; Steinman et al., 1995), these studies often use displays where the illusion is induced by a single box and that may conflate PGM and flashILM.

Experiment 2

Experiment 1 suggested that rILM was best measured by removing the bar beginning earlier in time and anchored so that it was completely removed during the flash 16.7 ms after flash onset. In addition, flashILM could be measured by removing

the bar beginning earlier in time but anchoring to the point 50 ms after flash onset, or when the flash ended. What is unclear, however, is whether rILM occurs because it is specifically locked to a point 16.7 ms after flash onset or because the flash offsets after the bar is removed. Moreover, it is unclear if flashILM occurs because the bar is fully removed after the flash offset, where there is no overlap with the flash, or because it is fully removed 50 ms after flash onset.

Experiment 2 examined these questions by replicating the rILM and flashILM conditions from Experiment 1, where the bar was removed beginning earlier in time and full removal was anchored to either 16.7 ms (rILM E16) or 50 ms (flashILM E50) post flash onset, and where the flash duration was 50 ms. Two additional flash durations were included, a 16.7-ms flash (one screen) and an 83.3-ms flash (five screens). With the 16.7-ms flash, we could determine if rILM still occurred in the absence of flash–bar overlap, which would indicate that underlying rILM is a process sensitive to the temporal sequence of the flash onset and bar removal. If rILM did not occur, then it would suggest that overlap between bar removal and the flash may be the critical display feature that produces rILM. If rILM does not occur in the 83.3-ms flash condition when anchored to the 16.7-ms point but did occur for flashes of 16.7-ms and 50-ms duration, then this would suggest the importance of the temporal interval between full bar offset and flash offset. If rILM only occurs in the 50-ms flash duration when removal is completed at the 16.7-ms interval, then rILM would appear to be sensitive to both the time between flash onset and flash offset.

When the bar removal was anchored to the 50-ms point, then flashILM should occur in all conditions if the temporal interval between flash onset and bar removal is the critical parameter of the display conditions, which is what is predicted by the attentional gradient explanation for flashILM. However, if the critical display feature is the fact the flash ends at or before the bar is fully removed, then the 83.3-ms flash should not produce flashILM, although it may produce rILM. On the other hand, if overlap is critical for rILM and the 50-ms temporal interval is important for flashILM, and rILM and flashILM are separate illusions, then the 83.3-ms flash condition, which contains both of these display features, should result in a summation of the conflicting flashILM and rILM illusions. In the case of a summation, the sign of ILM$_{area}$ would reflect which of the two illusions was the stronger.

Method

Participants

Of the 30 who volunteered to participate, five failed to complete the experiment, and one positioned their hands on the wrong keys, making their data uninterpretable, resulting in useable data being obtained from 24 participants (11 males,

13 females, mean age = 21.83 years, SD = 4.64, range: 17–35) for analysis. Participants were recruited from the University of Auckland student population. All participants reported having normal or corrected-to-normal vision. Handedness was assessed by the Edinburgh Inventory and indicated 21 were right-handed, two were left-handed, and one was ambidextrous (Oldfield, 1971). All participants were naïve to the purpose and predictions of the study. None of the participants had participated in Experiment 1. The study was approved by the University of Auckland Human Participants Ethics Committee. All participants provided informed written consent prior to participation.

Apparatus and stimuli

The same apparatus was employed as in Experiment 1. Stimuli were the same dimensions as in Experiment 1. Bar removal was performed to ensure the last segment was removed either one screen (16.7 ms) after flash onset or three screens (50 ms) after flash onset. Flash duration was either one screen (16.7 ms), three screens (50 ms), or five screens (83.3 ms) in duration. The conditions with the 50-ms flash duration exactly replicate the E16 and E50 conditions of Experiment 1, with the other conditions differing only in terms of the flash duration. All other aspects of the experimental procedure were the same. The temporal sequence of the display events may be seen in Fig. 10.

Design

The experimental design consisted of 3 flash locations (left, right, none) × 7 levels of real motion (slow left through to slow right, as in Experiment 1) × 3 flash durations (16.7 ms, 50 ms, and 83.3 ms) × 2 bar removal time points (16.7 ms and 50 ms

post flash onset), resulting in 126 combinations. There were 10 repetitions of each combination, for a total of 1,260 trials.

For statistical analysis, ILM_{area} and the dt_{ce} were calculated as in Experiment 1 with respect to a 3 × 2 design consisting of the three flash durations and two bar removal time points.

Procedure

The 1,260 trials were presented in a random sequence, and participants could take a self-timed break every 210 trials. The same instructions were given as in Experiment 1. Left and right responses were made on the < and > keys. Trials terminated without replacement if no response was made in 4,000 ms and were not considered during the analysis. The experiment required an average of 64.58 minutes to complete.

Results

After discarding trials with a decision time less than 200 ms (anticipations, 308, 1.02%), those with decisions times greater than 2,000 ms (distractions, 232, 0.77 %), and those for which an incorrect key or no key was pressed (invalid response, 91; 0.30 %), the remaining 29, 609 trials (97.91%) were retained for further analysis.

Percept scores

The mean percept scores can be seen in Fig. 11a–f. The ILM_{area} measure was calculated for each combination of the two anchor point times (one or three screens, 16.7 ms or 50 ms, following flash onset, coded as B16 or B50 for bar removed by 16 ms or 50 ms, respectively) and three flash durations (one, three, or five screens, 16.7 ms, 50 ms, or 83.3 ms, coded as F16, F50, and F83). Based upon single-sample t
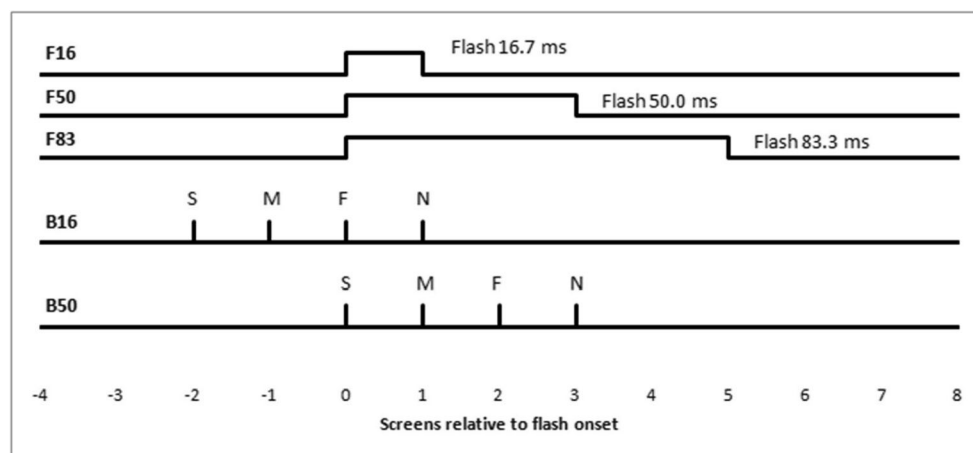

Fig. 10 Temporal characteristics of the display employed in Experiment 2 in terms of 16.7-ms screen-refresh cycles relative to the flash onset at zero. Top three lines indicate the time period over which the flash (left or right) was presented in the F16, F50, and F83 conditions, respectively. The lower two time lines indicate the B16 and B50 conditions,

respectively. Points on the bar time lines indicate frames where a bar segment could be removed. Bar removal was always completed at point N, and removal began on the S, M, F, or N frame for slow, medium, fast, and no real motion trials, respectively, for both left and right real motion directions
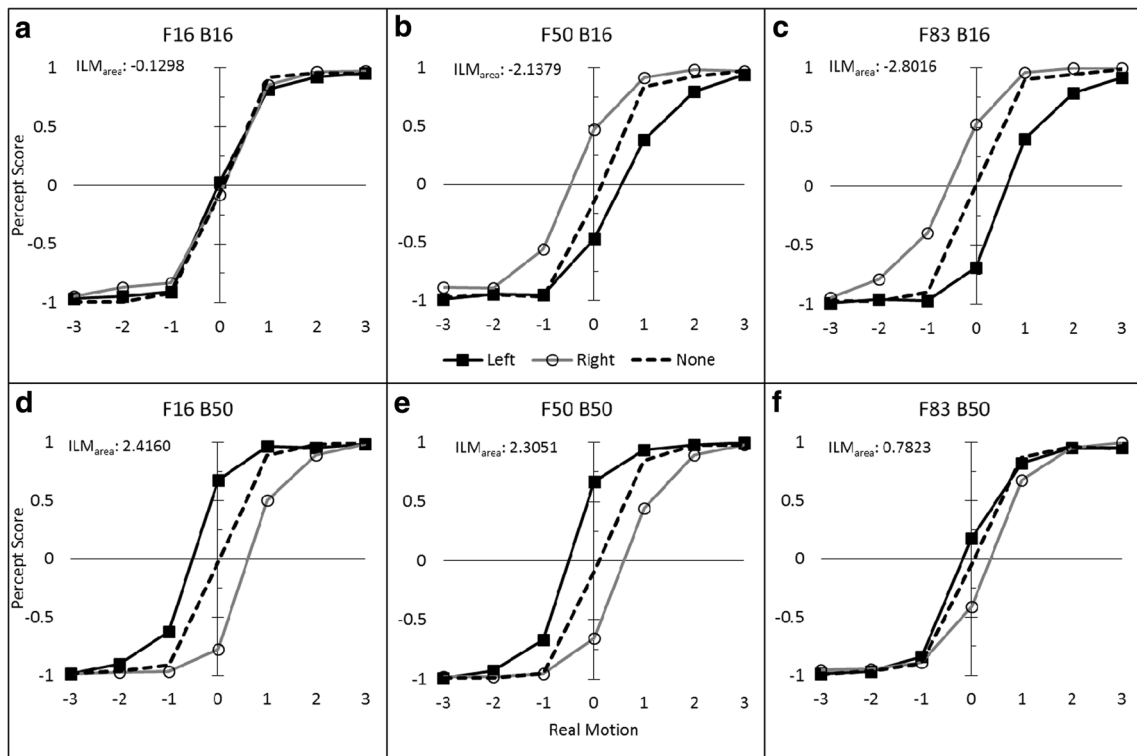
Fig. 11 Group mean percept scores for (**a**) 16.7-ms flashes with real motion that ends 16.7 ms after flash onset, (**b**) 50-ms flashes with real motion that ends 16.7 ms after flash onset, (**c**) 83.3-ms flashes with real motion that ends 16.7 ms after flash onset, (**d**) 16.7-ms flashes with real motion that ends 50 ms after flash onset, (**e**) 50-ms flashes with real motion that ends 50 ms after flash onset, and (**f**) 83.3-ms flashes with real motion that ends 50 ms after flash onset

tests, apart from the F16-B16 condition, $t(23) = -0.79$, $p = 0.44$, $M = -0.1298$, pH0|D = 0.78, positive evidence in favour of the null hypothesis, all of the remaining conditions showed an area measure significantly different from zero, $t(23) = -7.70, -8.80, 13.38, 13.62, 3.81$, all ps < .001, all pH0|D < 0.02, strong evidence against the null hypothesis, $M = -2.14, -2.80, 2.42, 2.31$, and 0.78, for conditions F50-B16, F83-B16, F16-B50, F50-B50, and F83-B50, respectively, indicating the presence of rILM in the F50-B16 and F83-B16 conditions and $_{flash}$ILM in the F16-B50, F50-B50, and F83-B50 conditions, and no illusion in the F16-B16 condition.

The two conditions showing rILM (F50-B16 and F83-B16; Fig. 12a) were then examined to determine if their ILM$_{area}$ measures were correlated after discarding data pairs with Cook's D that exceeded the criterion ($4/n$). The predicted relationship was confirmed, $r(20) = .84$, $p < .001$, pH0|D < 0.001, very strong evidence against the null hypothesis, two outliers. In addition, the area measures from condition F16-B50 and F50-B50 were also correlated, $r(21) = .47$, $p = .024$, pH0|D = 0.22, positive evidence against the null hypothesis, one outlier (see Fig. 12b). The average rILM$_{area}$ and average $_{flash}$ILM$_{area}$ were then calculated and tested for a relationship, which was not found, $r(21) = .08$, $p = .72$, pH0|D = 0.82, positive evidence in favour of the null hypothesis, one outlier

(see Fig. 12c). The sum of the average rILM$_{area}$ and $_{flash}$ILM$_{area}$ was then used to predict the area value for the F83-B50 condition, resulting in a significant correlation, $r(20) = .61$, $p = .003$, pH0|D = 0.03, strong evidence against the null hypothesis, two outliers (see Fig. 12d). While a stepwise regression with a $p < .05$ entry and $p > .1$ removal criterions only entered $_{flash}$ILM$_{area}$ as a predictor, $r(22) = .434$, $p = .03$, pH0|D = 0.2859, weak evidence against the null, $y = 0.588 \, _{flash}$ILM$_{area} - 0.605$, rILM$_{area}$ was close to the entry probability ($p = .07$), and would have remained in the model in a backwards removal procedure, $r(21) = .552$, $p = .02$, pH0|D = 0.2345, positive evidence against the null, $y = 0.476 \, _{flash}$ILM$_{area} + 0.253 \, $rILM$_{area} - 0.284$.

Decision times

The mean decision times can be seen in Fig. 13a–f. The decision-time congruency effect was calculated for each condition, and it was found to be significantly different from zero in all except the F83-B50 condition, $t(23) = -2.62, -7.65, -8.30, 6.34, 5.07$, and 1.58, $p = .015, < .001, < .001, < .001, < .001$, and $.127$, all pH0|D < 0.17, positive evidence against the null, except for F83-B50 with pH0|D = 0.58, weak evidence in favour of the null, $M = -20, -66, -74, 63, 52$, and 11
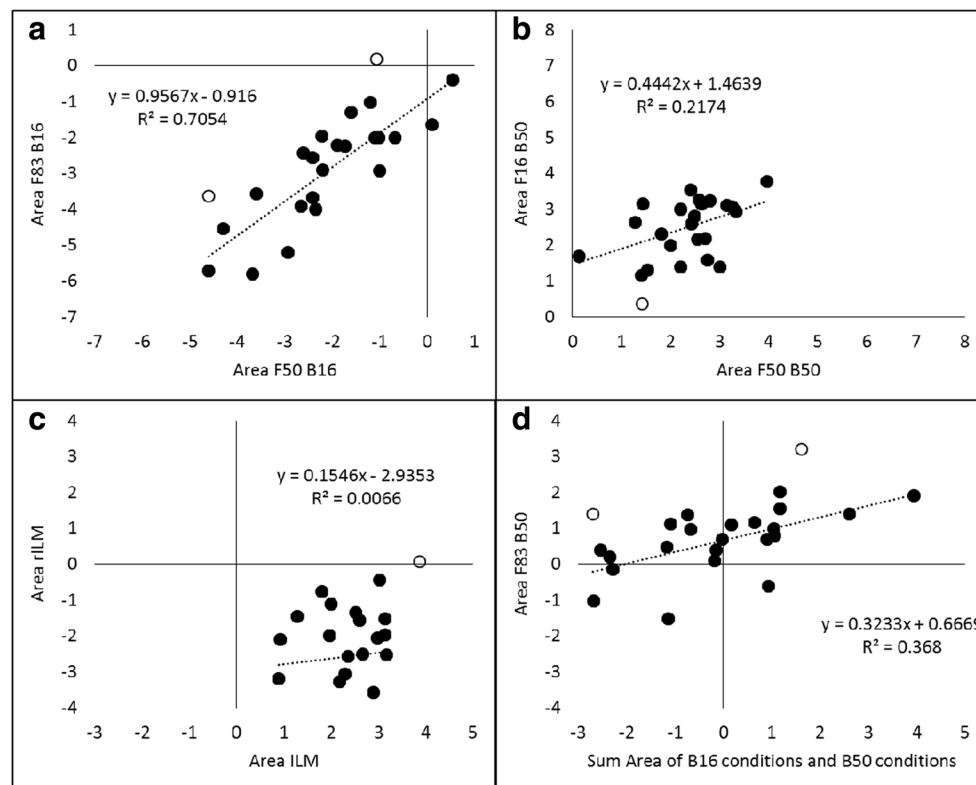
Fig. 12 Correlations of ILM_{area} between (**a**) rILM conditions F50-B16 and F83-B16; (**b**) $_{flash}$ILM conditions F16-B50 and F50-B50; (**c**) average of previous rILM_{area} and $_{flash}\text{ILM}_{area}$; and (**d**) the sum of a participant's average previous rILM_{area} and $_{flash}\text{ILM}_{area}$ and the ILM_{area} from the F83-B50 condition

ms, for the F16-B16, F50-B16, F83-B16, F16-B50, F50-B50, and F83-B50 conditions, respectively.

As in Experiment 1, the percept scores were fit by least squares to a log linear function scaled to the range −1 to +1 (Ha et al., 2017; Hamm, 2017; Han et al., 2016) in order to calculate the point of subjective equality for each series of data. The decision times were then plotted as a function of the distance from the PSE. As in previous studies, all conditions were well described by an exponential distance decay function (Ha et al., 2017; Hamm, 2017; Han et al., 2016), as shown in Fig. 14a–f.

Discussion

Examination of the ILM_{area} measure indicated that rILM occurred when the bar removal was anchored to 16.7 ms after the flash onset but only when the flash was 50 ms or 83.3 ms in duration. A backwards removal model suggested rILM may have been active in the F83-B50 condition, although the evidence is considered weaker as the stepwise model does not include rILM as a predictor. Regardless, when the flash was only 16.7 ms in duration, there was no evidence for rILM in the percept scores. This suggests that rILM may reflect a process or mechanism related to the overlap between the bar

removal and the flash rather than a process or mechanism that is time locked to occur very shortly after flash onset. In contrast, $_{flash}$ILM was found in all conditions where the bar removal was completed at 50 ms post flash onset, including when the flash turned off earlier (F16-B50), simultaneous (F50-B50), or after (F83-B50) complete bar removal, suggesting that $_{flash}$ILM is tied to a process or mechanism that builds over time and is active by 50 ms post flash onset. Again, in the condition where the bar removal was locked to the $_{flash}$ILM time window but in which the flash offsets after full bar removal, it appears that both rILM and $_{flash}$ILM were generated, although the evidence should be viewed as suggestive for this dual case. However, accepting this for the current time seems rational as the evidence tends to suggest there are two separate processes or mechanisms in operation, one that results in rILM due to flash–bar overlap and one that results in $_{flash}$ILM at 50 ms post flash onset. The display conditions of the F83-B50 meets both of these conditions, and the data are generally consistent with a combination of $_{flash}$ILM and rILM.

The decision-time congruency effect generally supported the conclusion that rILM and $_{flash}$ILM were occurring when there was overlap or when the bar was removed 50 ms post flash onset, respectively. The dt_{ce} suggested there may have been some rILM in the F16-B16 condition, although this could
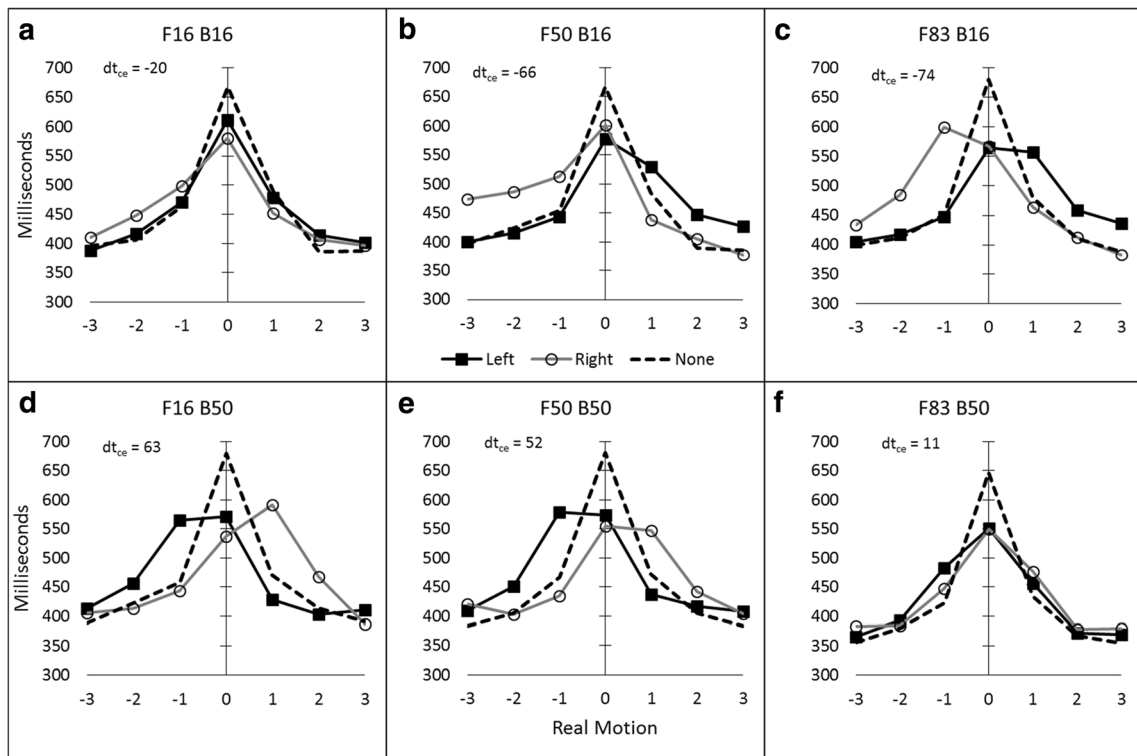
Fig. 13 Group mean decision times for (**a**) 16.7-ms flashes with real motion that ends 16.7 ms after flash onset, (**b**) 50-ms flashes with real motion that ends 16.7 ms after flash onset, (**c**) 83.3-ms flashes with real motion that ends 16.7 ms after flash onset, (**d**) 16.7-ms flashes with real motion that ends 50 ms after flash onset, (**e**) 50-ms flashes with real motion that ends 50 ms after flash onset, and (**f**) 83.3-ms flashes with real motion that ends 50 ms after flash onset
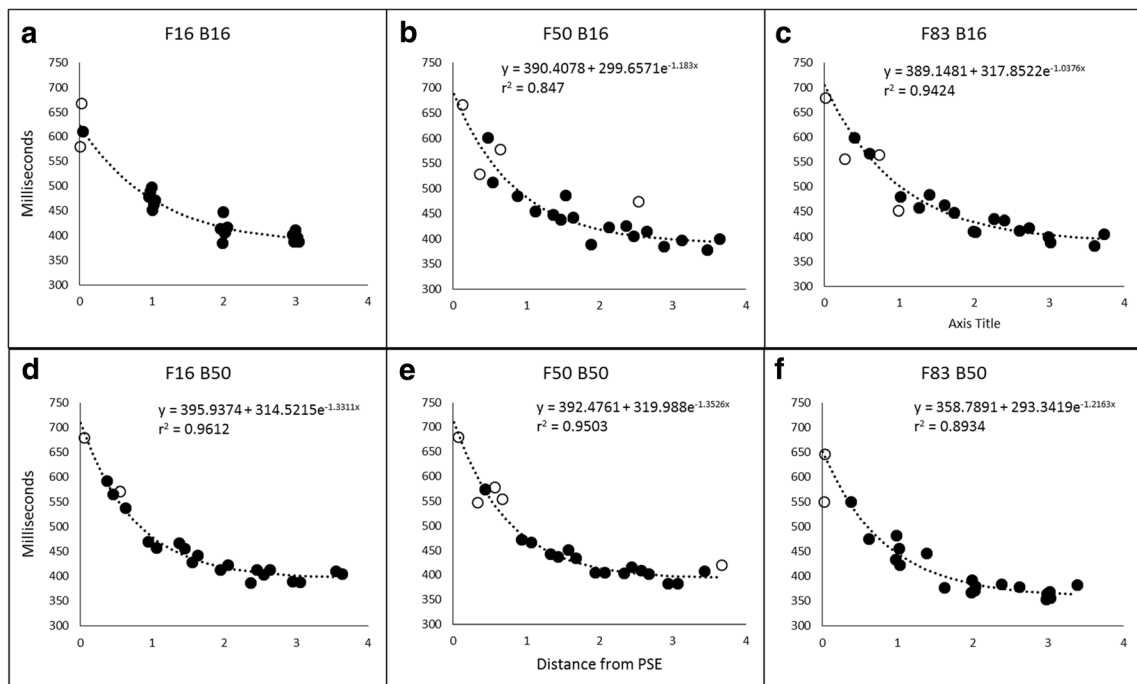

Fig. 14 Group mean decision times as a distance decay function from the point of subjective equality (**a**) 16.7-ms flashes with real motion that ends 16.7 ms after flash onset, (**b**) 50-ms flashes with real motion that ends 16.7 ms after flash onset, (**c**) 83.3-ms flashes with real motion that ends 16.7 ms after flash onset, (**d**) 16.7-ms flashes with real motion that ends 50 ms after flash onset, (**e**) 50-ms flashes with real motion that ends 50 ms after flash onset, and (**f**) 83.3-ms flashes with real motion that ends 50 ms after flash onset

reflect a tendency to respond more quickly on the side of the flash, as per the Simon effect (Umilta & Nicoletti, 1990).

In all cases, the decision times were well described by an exponential distance decay function away from the point of subjective equality. This suggests the location of the response boundary (Cartwright, 1941) shifts when opposite directions of illusory motion and real motion combine, which means the motion information is cancelling because conditions with real motion are being treated as if they do not contain motion. The alternative would be that when there are two possible and conflicting interpretations, one is suppressed and the other is perceived. The PSE would then reflect the point where either the real or illusory motion is equally likely to win perceptual preference. However, as the decision times indicate, responses to real motion in the absence of a flash and decision times to illusory motion alone (the no real motion with flash conditions) all produce faster responses than at the point of subjective equality. If the PSE simply reflected the point at which either the real motion or the illusory motion was perceived with equal probability, then the decision time should reflect the average of these two times and so should fall midway between them, which is inconsistent with the PSE being the slowest decision time (Crawford et al., 2010; Ha et al., 2017; Hamm, 2017; Han et al., 2016). In addition, when participants are given the option to respond 'no motion', this option should rarely be chosen and should not increase near the PSE, as the alternative explanation is based upon always seeing either the illusory or real motion. However, it has been shown that the no motion response increases near the PSE, providing further evidence against this alternative interpretation (Han et al., 2016).

While conditions that produced rILM (F50-B16 and F83-B16) were correlated with each other, and conditions that produced $_{flash}$ILM (F16-B50 and F50-B50) were correlated with each other, the average of these rILM and the average of these $_{flash}$ILM conditions were uncorrelated, suggesting rILM and $_{flash}$ILM are independent illusions, which can both be triggered simultaneously, as in the F83-B50 condition. The Bayesian analysis indicated that the data were in support of independence between rILM and $_{flash}$ILM, replicating the findings of Experiment 1 and previous findings of independence between $_{flash}$ILM and rILM (Han et al., 2016). In support of the individual participant correlational analysis, rILM appears governed by overlap with the flash, while $_{flash}$ILM appears to be linked to the temporal relationship between flash onset and the bar removal. This suggests that rILM may be a result of low-level visual features of the stimulus display, while $_{flash}$ILM may be related to exogenous visual attention (Ha et al., 2017). This would be consistent with the finding that the condition where there was sufficient time for the flash to attract exogenous attention but there was also the overlap between the flash and the bar

offset (F83-B50), the area measure was well predicted by the sum of an individual's rILM and $_{flash}$ILM scores, suggesting both mechanisms were operating and influencing the final motion percept. However, the multiple-regression analysis was less definitive on this, and while a removal procedure supported this interpretation, a stepwise procedure failed to enter rILM into the model. Notwithstanding this latter finding, the overall pattern of results, including those from the dt_{ce}, are interpreted as generally indicating that both rILM and ILM were active when the bar removal was anchored to the 50-ms time point and the flash overlapped with the bar removal.

If rILM arises as a result of the overlap, this could be explained by spreading subthreshold activation (Jancke et al., 2004), sustaining the near end of the existing bar and being stronger when the box is brightened. This increased activity would diminish quickly upon flash offset, making it less influential if there is no overlap between flash and bar offset. It should also be relatively constant, and not time dependent with respect to the flash onset. With prolonged presentation, however, it is possible that TAM-related processes may become active and the disappearing bar may be drawn into the box of similar luminance rather than into the brighter box. If TAM-based and attention-based ILM are both active in the F83-B50 condition, this may account for why the multiple-regression results are noisy with respect to including rILM in the model. It should be noted that because TAM predicts motion away from the brighter box, rILM seems unlikely to be related to TAM-related processes, but that is an empirical question for another day. Also, the fact that motion towards the flash is found with the F50-B16 condition, but overall the motion was away from the flash in the F83-B50 condition, means the illusory motion cannot be explained solely by contrast counter change (Hock & Nichols, 2010) because the contrast changes are identical in these displays. It must be emphasized, however, that this does not mean that contrast counter change does not produce, or contribute, to illusory motion, only that it cannot be the sole explanation. Whether contrast counter change results in its own unique illusion or is a description of the changes that occur during the object tracking processes involved in TAM remains an open question.

General discussion

In summary, the results of both Experiments 1 and 2 indicate that the rILM that occurs when a bar is removed during a luminance flash is unrelated to $_{flash}$ILM that occurs when the bar is removed at the 50 ms post flash onset. The display can activate rILM and $_{flash}$ILM at the same time, with the final motion percept reflecting the combined motion information. It seems that rILM is related to visual aspects of the display

and may require the bar to be removed while the flash is occurring and that the time since flash onset is of lesser importance. Conversely, $_{flash}$ILM appears to be more related to the time course of events beginning with the onset of the flash and seems less related to the specifics of the display configuration with respect to the low-level visual description, in that the flash can have offsetted earlier, simultaneous with, or after the bar has been removed. Previous studies have reported a decrease in illusory motion as the SOA is increased (Hubbard & Ruppel, 2011; Steinman et al., 1995), although it should be noted that these studies have used single box and bar presentations that may also invoke PGM. Experiment 1 indicates rILM is best measured by starting the bar removal earlier in time so as to ensure that full removal occurs 16.7 ms after flash onset, with the flash continuing for some amount of time following the bar's removal. It is unclear if rILM requires flash offset or not. In contrast, $_{flash}$ILM can be measured with bars that are time locked so that either full removal or the start of removal is locked to 50 ms after flash onset. It is, however, not determined what amount of time post flash onset results in the largest $_{flash}$ILM, as time-course studies have generally conflated $_{flash}$ILM and PGM. Finally, while $_{flash}$ILM has been shown to be unrelated to TAM as well as being unrelated to rILM, it is untested if rILM is or is not related to TAM.

There are some characteristics of rILM that appear at odds with a TAM explanation. With rILM, the offset-bar motion is away from the similar box and not into the similar box as it is with TAM (Tse, 2006). In addition, while TAM occurs with both onset and offset bars, rILM seems to only occur with offset bars and does not appear to occur with onset bars (Han et al., 2016). Further investigations into the properties of rILM, and comparisons of rILM to other forms of illusory line motion are necessary in order to determine what processes or mechanisms are responsible for its occurrence. Regardless, the current findings replicate the lack of a relationship between $_{flash}$ILM and rILM (Han et al., 2016), indicating they are two separate illusions that arise for different reasons and so require separate explanations. This points to the necessity to consider even small variations in display conditions when evaluating the results from studies of illusory line motion. It remains to be determined if rILM is related PGM, but if so, this would suggest that the mechanism underlying rILM and PGM is the low-level spreading of subthreshold activation (Jancke et al., 2004).

References

Cartwright, D. (1941). Relation of decision time to the categories of response. *American Journal of Psychology, 54*, 174–196.

Christie, J. (2014). Illusory line motion is not caused by object-differentiating mechanisms or endogenous attention. *Quarterly Journal of Experimental Psychology, 67*(12), 2293–2300. doi: https://doi.org/10.1080/17470218.2014.918633

Christie, J., & Klein, R. M. (2005). Does attention cause illusory line motion? *Perception & Psychophysics, 67*(6), 1032–1043.

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*(2/3), 327–332. doi: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*(10), 3121–3127. doi:https://doi.org/10.1016/j.neuropsychologia.2010.06.027

Faubert, J., & von Grünau, M. (1995). The influence of two spatially distinct primers and attribute priming on motion induction. *Vision Research, 35*(22), 3119–3130. doi:https://doi.org/10.1016/0042-6989(95)00061-4

Ha, H. Y., Li, D., Patten, B., & Hamm, J. P. (2017). The relationship between flash based illusory line motion and visual exogenous attention. *Canadian Journal of Experimental Psychology.* doi:https://doi.org/10.1037/cep0000122

Hamm, J. P. (2001). Object-oriented millisecond timers for the PC. *Behavior Research Methods Instruments & Computers, 33*(4), 532–539. doi: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. doi: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*(1), e87595. doi:https://doi.org/10.1371/journal.pone.0087595

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. doi: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 and Computers, 20*, 289–297.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993a). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*(9), 1219–1240.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993b). Visual attention revealed by an illusion of motion. *Neuroscience Research, 18*(1), 11–18.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993c). Voluntary and stimulus-induced attention detected as motion sensation. *Perception, 22*, 517–526.

Hock, H. S., & Nichols, D. F. (2010). The line motion illusion: The detection of counterchanging edge and surface contrast. *Journal of Experimental Psychology-Human Perception and Performance, 36*(4), 781–796. doi:https://doi.org/10.1037/A0016876

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*(4), 1133–1146. doi: https://doi.org/10.3758/s13414-010-0081-7

Jancke, D., Chavane, F., Naarman, S., & Girinvald, A. (2004). Imaging cortical correlates of illusion in early visual cortex. *Nature, 428*, 423–426.

Kanizsa, G. (1951). Sulla polarizzazione del movimento gamm [On the polarization of gamma motion]. *Archivo di Psicologia, Neurologia e Psichiatria, 3,* 224–267.

Kanizsa, G. (1979). Organization in vision: Essays on gestalt perception. New York, NY: Praeger.

Masson, M. E. J. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavor Research Methods, 43*(3), 679–690. doi: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*(2), 322–328.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9,* 97–113.

Raftery, A. E. (1995). Bayesian model selection in social research. *Sociological Methodology, 25,* 111–163. doi:https://doi.org/10.2307/271063

Schmidt, W. C., & Klein, R. M. (1997). A spatial gradient of acceleration and temporal extension underlies three illusions of motion. *Perception, 26*(7), 857–874.

Shimojo, S., Miyauchi, S., & Hikosaka, O. (1997). Visual motion sensation yielded by non-visually driven attention. *Vision Research,*

37(12), 1575–1580. doi:https://doi.org/10.1016/S0042-6989(96)00313-6

Skottun, B. C. (2011). Amplitude spectra of line-motion stimuli. *Perception, 40*(6), 656–673. doi:https://doi.org/10.1068/P6905

Steinman, B. A., Steinman, S. B., & Lehmkuhle, S. (1995). Visual attention mechanisms show a centre-surround organization. *Vision Research, 35*(13), 1859–1869.

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*(2), 766–773. doi:https://doi.org/10.1016/j.neuroimage.2005.12.029

Umilta, C., & Nicoletti, R. (1990). Spatial stimulus-response compatibility. In R. W. Proctor & T. G. Reeve (Eds.), Stimulus response compatibility (pp. 89–115). North Holland, The Netherlands: Elsevier Science.

von Grünau, M., & Faubert, J. (1994). Intraattribute and interattribute motion induction. *Perception, 23*(8), 913–928. doi:https://doi.org/10.1068/p230913