

“Don't fence me in!”: Examining the source of bias within Müller-Lyer target aiming

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ABSTRACT

The Müller-Lyer illusion distorts the perceived length of a line shaft based on the relative orientation of tail-ends. This illusion has been heavily adapted to evaluate the visual processes underlying both perception and action. While much of the evidence suggests an influence of this illusion on actions such as manual aiming, the debate surrounding this influence continues. Indeed, it is possible that the tail-ends independently steer extra-retinal inputs regarding target position, which could inadvertently bias any aiming attempts. To this end, participants completed rapid aiming movements toward a series of tail configurations (tails-in, tails-mid, tails-out, tails-combined) either with or without the line shaft; thus nullifying any misperception in length that is typically caused by the illusion (Exp. 1). The findings showed differences in movement displacement that were effectively shifted toward the tails, irrespective of whether there was a shaft present. To extend these findings, we additionally introduced configurations whose tails were oriented left and right (tails-left, tails-right) (Exp. 2). As well as replicating the previously highlighted differences in movement displacement, we also showed a shift in the movement direction toward the tail-ends. Each of these movement effects were isolated to the very end of the movement rather than the early portions. While these findings do not disqualify the influence of illusion configurations on action, they nonetheless indicate a different origin to the relative metrics that are suggested to underlie perception.

1. Introduction

The Müller-Lyer illusion refers to a perceived difference in the length of a line shaft depending on whether it is flanked by line tails facing inward or outward (for examples, see [Figs. 1 and 3](#)). Specifically, the length is perceived to be shorter for the tails-in configuration, and longer for the tails-out configuration. Since its inception, this illusion has been heavily adapted within a wide variety of fields including cognitive psychology, behavioral neuroscience, and visual psychophysics. One such line of interest surrounds how it is that this illusion may separately influence perception and visually-guided action. According to the perception-action model, an illusion may bias perception (e.g., line-length judgment) in ways that are not equally reflected in action (e.g., aiming amplitude or grasp aperture) ([Milner and Goodale, 1995, 2008](#)). This model is explained by the notion of functionally distinct visual

neural pathways; that is, a ventral pathway coding for the allocentric (relative) metrics to give rise to an illusion in perception, while a dorsal pathway coding for the egocentric (absolute) metrics effectively nullifies the illusion in action (see also, [Ungerleider and Mishkin, 1982](#)).

However, several alternative models have been proposed in response to the mixed and sometimes contradictory findings regarding the influence of illusions on action. Namely, the single representation view contends that perception and action share the same visual input, and thus illusions should influence action in a direction that is near entirely consistent with the perceptual bias ([Franz, 2001](#); [Bruno et al., 2008](#); [Bruno and Franz, 2009](#)). Meanwhile, the planning-control model suggests that any illusion-induced bias within action should only unfold within the initial movement phase as a product of prior planning (e.g., early reaching-to-grasp), and not toward the end of movement as it becomes more visually-guided (e.g., final adjustments to grip aperture)

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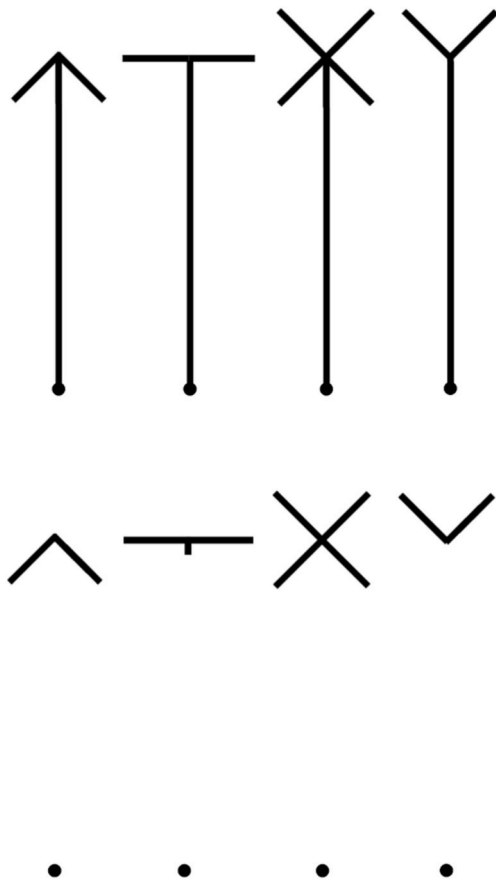


Fig. 1. Illustration of the target stimuli including tails-in, tails-mid, tails-combined, and tails-out (in order from left-to-right) either with a shaft (upper panel) or no shaft (lower panel).

(Glover and Dixon, 2001, 2002). In contrast, the multiple process model indicates that illusion-induced biases within action should increase toward the end of the movement as the limb position is progressively adjusted to close the space to the target (e.g., time after peak velocity) (Handlovsky et al., 2004; Mendoza et al., 2005; Mendoza et al., 2006; Heath et al., 2007; see also, Elliott et al., 2010).

Due to this discrepancy between the proposed models and subsequent research findings, it has become difficult to categorically attest to the influence of illusions on action, as well as the related visual neural processes. Instead, there is an emerging consensus that rather than the (lack of) effects of illusions within perception and action highlighting a dissociation in visual neural pathways and their related allocentric/egocentric reference codes, they are effectively a by-product of a separate set of task constraints (Smeets and Brenner, 1995, 2001; Smeets et al., 2002; see also, Roberts et al., 2021). Specifically, a perceptual bias caused by the Müller-Lyer illusion would be typically related to length, where the orientation of the adjacent tails with respect to the shaft would yield a misperception in the shaft's length. However, any indication of a bias within action toward the Müller-Lyer illusion could be alternatively related to the perceived position of the target in space that is independent of shaft length.

In support of this argument, findings have indicated a difference in the magnitude of biases inflicted separately by perceived length and position of endpoints within the Brentano illusion ($\leftarrow \rightarrow$ – $\leftarrow$) (a variation of the Müller-Lyer illusion) (Mack et al., 1985; see also, Post and Welch, 1996). In a similar vein, it has been shown that the biases within action toward the Judd illusion ($\leftarrow \leftarrow$) (length-independent) were highly similar to those for the Müller-Lyer illusion (length-dependent) (Glazebrook et al., 2005). Moreover, it has been

shown that biases within action toward a Müller-Lyer configuration may be increased when gaze is fixated nearer to the start, thus capturing more on the shaft length as opposed to the end-target position (Gentilucci et al., 1997; Binsted and Elliott, 1999; for similar effects using the vertical-horizontal illusion, see Yan and Hondzinski, 2021).

These findings are somewhat aligned with a separate line of research surrounding the precise configural properties manifesting in the Müller-Lyer illusion (Coren, 1986). Namely, it is suggested that the perceived 'centroid' within a surround configuration (e.g., Müller-Lyer tails) may steer extra-retinal input—courtesy of an efference copy (i.e., copy of the oculomotor command) and oculoproprioception (i.e., the position of the eye within the socket)—causing a bias in perception and action (see also, Binsted and Elliott, 1999). This concept may be at least partially explained by the integration or summation of neural excitations that manifest from the series of local details comprising a configuration (Bulatov et al., 2009; see also, Bulatov et al., 2011, 2022). To elucidate, the 'centroid' appears near the geometrical centre of a composition of individual figural elements, and thus in between the diverging and converging ends of the set of tails comprising the Müller-Lyer illusion. In other words, the 'centroid' would be located under the shaft end for the tails-in configuration (rendering a 'short' percept), and beyond or over the shaft end for the tails-out configuration (rendering a 'long' percept). Consequently, by introducing extraneous objects to a Müller-Lyer configuration that effectively opposes the misperceived length or position (e.g., $\bullet \leftarrow \rightarrow \bullet$), it is possible to near reverse any bias and nullify the illusion (Searleman et al., 2005). Of interest, these subtle variations in configuration, and their subsequent influence on perception and action may be at least partially attributed to Gestalt-based grouping principles (for a similar argument, see Haffenden and Goodale, 1998, 2001; Adam et al., 2006; Roberts et al., 2021) including features of proximity, similarity, continuation and closure (Coren and Girgus, 1980). Within the context of the Müller-Lyer illusion, it is the feature of closure that may be of most interest; that is, the capacity to bridge gaps and bind separate local details to effectively form a single or unified pattern. In this regard, it is possible that the adjacent tail-ends of the Müller-Lyer configuration may be perceptually grouped together, which could subsequently manifest as a perceptual bias.

To this end, we aimed to more closely examine the configural properties that govern the influence of the Müller-Lyer illusion on action. Specifically, we systematically manipulated the configuration in order that the shaft could no longer be seen relative to the orientation of the tails, thus rendering an absence of the allocentric cues to misperceive the shaft's length. That is, manual aiming movements were directed toward the vertex of a set of lines that comprised either a typical Müller-Lyer configuration including a shaft, or no shaft with only the tails present. The tails themselves were oriented to elicit a shift in position either solely in the primary axis (i.e., length) (Experiment 1; see Fig. 1), or additionally in the secondary axis (i.e., perpendicular direction) (Experiment 2; see leftward and rightward pointing configuration in Fig. 3). In line with the importance of the perceived endpoint target position, and independent of any misperception of length, it was broadly predicted that movement endpoints would be consistent with the direction or orientation of the tails, while doing so regardless of whether the shaft was present.

2. Experiment 1

2.1. Introduction

The notion of functionally distinct visual neural pathways may suggest that it is the degree of allocentric coding within action, and the related misperception of length, that may determine the influence of the Müller-Lyer illusion (e.g., perception-action model [Milner and Goodale, 1995]; planning control model [Glover and Dixon, 2001, 2002]). Alternatively, it is the bias inflicted on the target position in space, independent of length, that may primarily cause an influence of

the Müller-Lyer configuration on action (Mack et al., 1985; Post and Welch, 1996; Glazebrook et al., 2005).

Therefore, we investigated the configural properties of the Müller-Lyer illusion that may cause an effect within manual aiming. To do this, we systematically manipulated the allocentric cues that typically steer a bias in the perception of length by presenting the tails-in and tails-out configurations either with or without a shaft. To elucidate, with respect to the typical Müller-Lyer arrangement consisting of a shaft, the absence of a shaft may nullify any illusion pertaining to length, although the orientation of the tails would continue to provide the same endpoint position information (e.g., Coren, 1986; Bulatov et al., 2009). These line configurations were also compared with experimental control stimuli including the tails facing mid-way and a combination of tails-in and tails-out (Fig. 1). While these control configurations should technically no longer pose any bias in the perception of length regardless of whether they were coincident with or without a shaft, the former tails-mid configuration was incorporated owing to its tendency to cause an undershoot of the target vertex (e.g., Mack et al., 1985; Grierson and Elliott, 2009a, b; for a detailed explanation, see Roberts et al., 2013).

In line with the view of biases in action being contingent upon endpoint position information (see also, Coren, 1986), it was predicted that there would be a shorter-amplitude movement for tails-in and longer-amplitude movement for tails-out, which would be independent of any influence of shaft. It was also predicted that there would be a shorter-amplitude movement for tails-mid compared to tails-combined and tails-out. Moreover, in order to evaluate whether these effects could be attributed to offline planning and/or online control, we also assessed movement displacement at kinematic landmarks that occupied various points throughout the entire trajectory. The logic being that if any bias was attributed to prior planning, then we would anticipate an effect at the early landmarks (i.e., peak acceleration, peak velocity, peak negative acceleration) (e.g., planning-control model [Glover and Dixon, 2001, 2002]), while any bias related to visually-guided control would assume an effect later on (i.e., movement end) (e.g., multiple process model [Elliott et al., 2010, 2017]).

2.2. Method

2.2.1. Participants

Nineteen participants from a university community agreed to take part in the study (age range = 18–40 years, non-neurodiverse, right-hand dominant [self-reported], 9 males, 9 female, 1 undisclosed). All participants reported normal or corrected-to-normal vision, and no upper extremity musculoskeletal issues. The study was designed and conducted in accordance with the Declaration of Helsinki, and approved by the McMaster University Research Ethics Board.

2.2.2. Apparatus, task and procedure

The experimental set-up comprised a standard LCD monitor (57-cm height x 34-cm width, 60-Hz temporal resolution, 1024 x 768-pixel spatial resolution) that was covered by 5-mm sheet of Plexiglas. The monitor was placed and secured vertically inside an in-house designed open-face wooden box (58.7-cm height x 38-cm width x 10.5-cm depth). This box was secured with bench vice clamps to a horizontal steel ledge that was held at or near individual waist-heights by a vertical stand (for a similar set-up, see Roberts et al., 2016).

The stimuli were displayed and controlled using E-prime software (v. 2.0; Psychology Software Tools Inc., Sharpsburg, PA, USA). Stimuli consisted of a series of black figures on a white background. These figures involved a small dot (10-mm diameter) near the bottom of the display, and solid lines (5-mm thick) configured to form ‘tails’ (100-mm length) either alone or at the distal end of a single shaft that extended along the mid-sagittal axis (180–320-mm length). The tails were oriented at 45, 90, or 135-deg angles with respect to the shaft location, which had the effect of the tails facing inward, mid-way or outward, respectively. These orientations produced four separate configurations

including tails-in, tails-mid, tails-combined, and tails-out (Fig. 1). When the shaft was absent, then the tails were simply present on their own in space. Alternatively, when the shaft was also present, then the tails-in and tails-out stimuli appeared as a ‘half’ or amputated version of the typical Müller-Lyer configuration; that is, with the shaft length continuing to appear perceptually small and long, respectively. The tails-mid and tails-combined represented alternative forms of an experimental control stimulus for the aforementioned illusion.

Participants wore a small finger-plectrum (‘banjo pick’) on the tip of the right index finger with an infrared emitting diode attached, which was then detected by an Optotrak 3020 motion capture system (Northern Digital Instruments Inc., Waterloo, ON, Canada). This system was triggered for each individual trial via a custom serial port connection to a local computer that was running the experiment. Trials were recorded for a 3-sec duration at a rate of 200 Hz (600 frames).

Participants stood upright and looking down toward the aiming surface. They were instructed to move their right index finger as quickly and accurately as possible along the mid-sagittal axis toward the vertex or intersection of the shaft and tail lines. Participants would indicate that they were ready to aim by first having the index finger make contact with the surface over the dot near the bottom that represented the home position. After a randomly selected foreperiod (800, 975, 1150, 1325, or 1500 ms), one of the line configurations appeared as the target, prompting the aiming movement. At this juncture, participants would need to move the index finger by lifting the limb and aiming forward without any sliding, before making contact with the surface once again at the point of terminating the movement near the target position. Each trial was recorded for 3 s to ensure there was sufficient time for participants to initiate and complete the required movement. Therein, the configuration was extinguished, and only the home position was presented once again to prepare for the next trial.

A brief familiarisation was provided for participants to experience the aiming task with each of the line configurations. The target positions were calibrated both before and after the experimental trials by recording participants’ index finger position when placed directly over the vertex of the shaft and tail lines that comprised each of the configurations. For the experimental trials, target amplitudes and configurations were randomized, while the presence or absence of the shaft was counter-balanced among participants. There were 10 trials for each of the possible target configurations, equating to a total of 180 trials. There was a short break (approx. 5 mins) after completion of half the trials (90 trials), with a further option for participants to take a break at any time during the trial protocol if ever they preferred.

2.2.3. Data management and analysis

Three-dimensional position data captured by the Optotrak system were filtered using a dual-pass Butterworth filter with a 10 Hz low-pass cut-off frequency to the order of 2 courtesy of the signal processing toolbox within Matlab (The MathWorks Inc., Natick, MA). These position data were then double-differentiated using the three-point central difference method to obtain velocity and acceleration profiles, respectively. Movement onset was defined as the absolute time when velocity within the primary direction of movement (y-axis) reached >10 mm/s for a duration of at least 40 ms. Subsequently, movement termination was defined as the absolute time when velocity reached within <10 mm/s and >-10 mm/s for at least 40 ms. Furthermore, the absolute times marking peak acceleration, peak velocity and peak negative acceleration were identified to further demarcate any effects to off-line planning and/or on-line control processes (see Khan et al., 2003, 2006; Roberts and Grierson, 2021).

Dependent measures of interest included reaction time (i.e., time between target and movement onset), movement time (i.e., time between the defined start and end of the movement) and constant error (CE) (i.e., signed difference in position between the movement endpoint and target vertex; negative [-] value indicates an undershoot). Moreover, we also extracted displacement at kinematic landmarks including

peak acceleration, peak velocity, peak negative acceleration and movement end.

A sub-set of the data that featured all of possible target configurations at a set amplitude (250 mm) were isolated subject to an inferential statistical analysis (80 trials). Trials were excluded if reaction time was <100 ms, movement time was <100 or >1000 ms, or movement amplitude <50% of the target distance were removed prior to the analysis as they were regarded as a product of a processing artefact or outlier (3.48% trials). Reaction time, movement time, and constant error were analysed using a two-way repeated-measures Analysis of Variance (ANOVA) with factors of shaft (present, absent) and configuration (tails-in, tails-mid, tails-combined, tails-out). The equal variance of differences assumption (Sphericity) was evaluated using Mauchly test. If the Sphericity assumption was violated, then the Greenhouse-Geisser adjusted value was adopted when Epsilon (ϵ) <.75, although the Huynh-Feldt adjusted value was adopted when it was $\geq .75$ (original uncorrected degrees-of-freedom are reported). In the event of a significant factorial interaction, then these were decomposed using simple effect analyses (using the error mean square and degrees-of-freedom from the original omnibus analysis). If there was a significant effect involving two or more means, then follow-up pairwise comparisons were conducted using the Holm-Bonferroni adjustment.

Meanwhile, the displacement at kinematic landmarks were analysed using Multivariate Analysis of Variance (MANOVA) (Wilks' λ) with each of the landmarks being entered as the dependent measures, and shaft and configuration as the repeated-measures factors. If there was a significant effect, then follow-up univariate ANOVAs were conducted on each level of kinematic landmark, which were again corrected using the Holm-Bonferroni adjustment. Significance was declared at $p < .05$, although alternative and more conservative criterion p-values were reported whenever the Holm-Bonferroni adjustment was applied. The effect size of interest was partial eta squared (η_p^2).

2.3. Results and discussion

For reaction time, the main effect of shaft approached conventional levels of significance ($F[1,18] = 3.94$, $p = .063$, $\eta_p^2 = .18$) indicating a shorter time to initiate movement for the shaft ($M [\pm SD] = 265$ ms [± 39]) compared to no shaft ($M [\pm SD] = 276$ ms [± 47]). There was no significant main effect of configuration, ($F[3,54] = 1.98$, $p = .13$, $\eta_p^2 = .10$), nor an interaction between shaft and configuration ($F[3,54] = 2.40$, $p = .12$, $\eta_p^2 = .11$). For movement time, there were no significant main, nor interaction effects ($F_s = .41$ – 1.81 , $p_s = .20$ – $.99$, $\eta_p^2 = .00$ – $.09$) (*grand M* [$\pm SD$] = 501 ms [± 81]). As a result, any effects of the configuration on subsequent measures could not be attributed to differences in movement preparation and/or overall movement duration, respectively.

For CE, there was no significant main effect of shaft ($F[1,18] = .70$, $p = .41$, $\eta_p^2 = .04$), although there was a significant main effect of configuration ($F[3,54] = 46.41$, $p < .001$, $\eta_p^2 = .72$),¹ and a significant interaction between shaft and configuration ($F[3,54] = 3.93$, $p = .01$, $\eta_p^2 = .18$) (Fig. 2). However, simple effect analyses on each level of shaft revealed a significant main effect of configuration for both the shaft (F

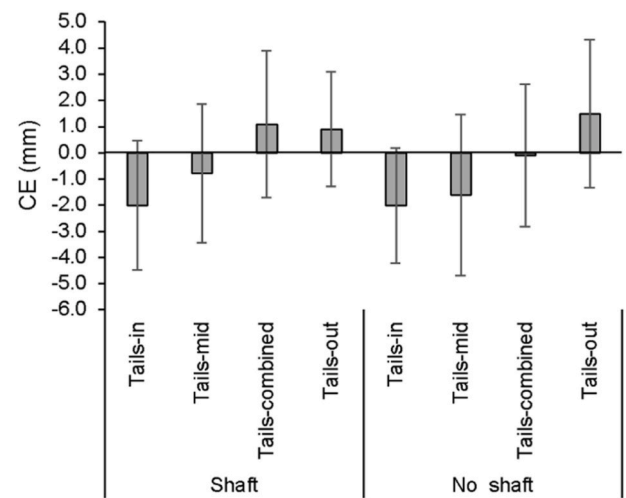


Fig. 2. Mean CE as a function of shaft and configuration (error bars represent the standard deviation).

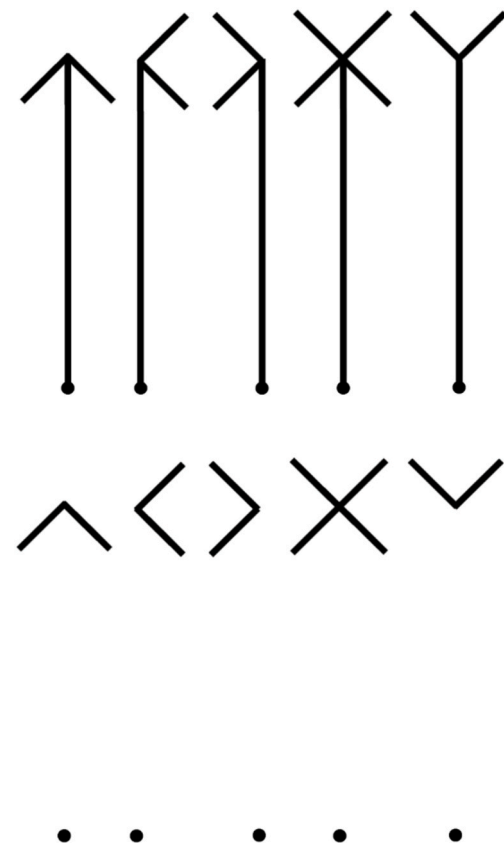


Fig. 3. Illustration of the target stimuli including tails-in, tails-right, tails-left, tails-combined, and tails-out (in order from left-to-right) either with a shaft (upper panel) or no shaft (lower panel).

[3,54] = 14.92, $p < .001$, $\eta_p^2 = .60$) and no shaft ($F[3,54] = 31.25$, $p < .001$, $\eta_p^2 = .64$).

Subsequent post hoc analysis on the shaft data revealed that the limb movement was terminated significantly shorter of the target for tails-in compared to tails-mid ($p < .025$), tails-combined ($p < .008$) and tails-out ($p < .010$), while tails-mid was also significantly shorter than tails-combined ($p < .017$) and tails-out ($p < .013$), although there was no significant difference between tails-combined and tails-out ($p > .05$). For the no shaft data, the limb movement was terminated significantly

¹ We explored the potential variance between participants as a result of the unintended alteration in target amplitude (200, 250 mm). While an ideal solution may be to run a linear mixed model with amplitude as a random factor, we were unable to do this for a number of reasons. That is, the target amplitude comprised only of two levels with no variance, and the aiming movement amplitude was a numerical covariate when it must be categorical. Therefore, we alternatively converted individual participant movement amplitudes into z-scores with respect to participants' own allocated or nominal target amplitude (i.e., participant mean movement amplitude – sample mean pooled across target amplitude/sample SD pooled across target amplitude) and ran the same ANOVA (general linear model) as the other main analysis.

shorter of the target for tails-in and tails-mid compared to tails-combined ($p < .010$ and $p < .025$, respectively) and tails-out ($p < .008$ and $p < .013$, respectively) with no significant difference between tails-in and tails-mid ($p > .05$), while tails-combined was significantly shorter than tails-out ($p < .017$).

For displacement at kinematic landmarks, the multivariate analysis revealed no significant main effect of shaft ($\Lambda = .58$, $F[4,15] = 2.75$, $p = .067$, $\eta_p^2 = .42$), although there was a significant main effect of configuration ($\Lambda = .26$, $F[12,135] = 7.39$, $p < .001$, $\eta_p^2 = .36$) (Table 1). There was no interaction between shaft and configuration ($\Lambda = .84$, $F[12,135] = .76$, $p = .69$, $\eta_p^2 = .06$). Further univariate analysis at each level of kinematic landmark indicated no significant main effect of configuration at peak acceleration ($F[3,54] = 1.89$, $p = .14$ [$>.05$], $\eta_p^2 = .10$), peak velocity ($F[3,54] = 2.20$, $p = .11$ [$>.025$], $\eta_p^2 = .11$), and peak negative acceleration ($F[3,54] = 3.30$, $p = .03$ [$>.017$], $\eta_p^2 = .16$), although there was a significant main effect of configuration at movement end ($F[3,54] = 35.11$, $p < .001$ [$<.013$], $\eta_p^2 = .66$). Subsequent post hoc analysis at movement end revealed a significantly shorter displacement for tails-in compared to tails-mid ($p < .025$), tails-combined ($p < .010$) and tails-out ($p < .008$). Furthermore, there was a significantly shorter displacement for tails-mid compared to tails-combined ($p < .017$) and tails-out ($p < .013$). Finally, there was a significantly shorter displacement for tails-combined compared to tails-out ($p < .05$).

In summary, there was a shorter movement amplitude for the tails-in compared tails-mid, tails-combined and tails-out. At first glance, these findings may suggest an illusion-induced bias, where the aiming movement was consistent with the direction of the illusion (e.g., Bruno et al., 2008; Bruno and Franz, 2009). However, it is important to note that there was also a shorter amplitude for the tails-mid compared to tails-combined, which were each unrelated to our principle concern of the Müller-Lyer illusion. Likewise, the aforementioned biases unfolded regardless of the shaft suggesting they were unrelated to any misperceived shaft length (see also, Haffenden and Goodale, 1998; 2001; Roberts et al., 2021). Instead, we suggest it was related to position information pertaining to the orientation of the tails, which may inadvertently steer the oculo-manual system away from the target vertex and toward the tail-ends (Coren, 1986; Glazebrook et al., 2005; see also, Coren and Girgus, 1980).

What's more, these effects manifested more toward the end of the movement as opposed to the earlier portions. This finding is consistent with the suggestion from the multiple process model that the influence of a target illusion should grow as the movement is progressively adjusted to close the separation between the limb and target positions (Elliott et al., 2010, 2017). This is not to say that the influence of an illusion on action is isolated to the emergence of delayed online control processes (e.g., >120 ms; Zelaznik et al., 1983; Cressman et al., 2006; Oostwoud Wijdenes et al., 2014; for a review, see Sarlegna and Mutha, 2015), but only that it coincidentally unfolds within this particular portion of the movement (for a similar argument, see Blinch et al., 2012).

3. Experiment 2

3.1. Introduction

The findings from Experiment 1 suggest that the bias exhibited within movement toward a Müller-Lyer configuration is not necessarily caused by the orientation of the tails relative to the line shaft, but it is alternatively independent of the line shaft. To corroborate this suggestion, we sought to replicate and elaborate upon these results using a new sample of participants and an extended set of configurations.

Specifically, in addition to the original tails-in, tails-combined and tails-out target configurations, we introduced tail orientations that could possibly induce biases within the secondary direction that runs perpendicular to the primary movement axis. That is, we had

participants aim toward leftward and rightward oriented tails (Fig. 3), presented again either with or without a shaft. In so doing, we were also able to capture the direction component of movement that is separate from the amplitude component, and thus unrelated to perceived shaft length (see Messier and Kalaska, 1999; Sainburg et al., 2003). In this regard, if there was continued bias that was extended into the secondary direction, then it would more strongly favour the role of a perceived endpoint position, rather than a misperceived shaft length.

Consistent with the view of the endpoint tail orientation being key to any bias caused by a Müller-Lyer configuration within action, then it was predicted that movement amplitudes would shift simply according to the direction of the tail-ends. That is, we should find movements that are shorter for tails-in, longer for tails-out, rightward for tails-right, and leftward for tails-left. Moreover, in order evaluate the influence within offline planning and online control, we also assessed displacement at kinematic landmarks. In line with the findings from Experiment 1, and the influence of target configuration on late limb-target control (Elliott et al., 2010, 2017), we predicted that any bias would be primarily found at the end of the movement following visually-guided control toward the target.

3.2. Method

3.2.1. Participants

Fifteen participants from a university community agreed to take part in the study (age range = 18-40 years, non-neurodiverse, right-hand dominant [self-reported]). All participants reported normal or corrected-to-normal vision, and no upper extremity musculoskeletal issues. The study was design and conducted in accordance with the Declaration of Helsinki, and approved by the McMaster University Research Ethics Board.

3.2.2. Apparatus, task and procedure

The experimental set-up was the same as Experiment 1 including the stimulus presentation and aiming surface. However, the stimuli featured tails presented either alone, or at the distal end of a shaft extending to a short (250 mm) or long (350 mm) amplitude. The tails were reoriented to effectively face inward, rightward, leftward or outward. These tail orientations produced five separate line configurations including tails-in, tails-right, tails-left, tails-combined and tails-out (Fig. 3). Once again, when the shaft was absent, then the tails were simply present on their own in space, at the specified amplitude from the home position. Alternatively, when the shaft was also present, then the tails-in and tails-out stimuli appeared as a "half" or amputated version of the typical Müller-Lyer configuration, and the tails-combined provided an experimental control stimulus for the aforementioned illusion (i.e., no misperception of shaft length). The previous tails-mid was no longer of interest, and in order to limit the number of trials, then this target was excluded from the present experiment. Meanwhile, the tails-right and tails-left stimuli were intended to shift the visual content and movement direction right and left, respectively.

Participants were tasked with pointing the right index finger forward along the mid-sagittal axis "as quickly and accurately as possible" to aim at the target formed by the vertex or intersection of the shaft and tail lines that comprised the different configurations. The subsequent data collection and trial events were the same as Experiment 1.

There was a brief familiarisation involving each one of the line configurations, as well as calibration trials as described in Experiment 1. The experimental trials were randomized with respect to the order of the target amplitudes, line configurations and shaft presence. There were 10 trials for each possible target, equating to a total of 200 trials. There was a short break (approx. 5 mins) after completion of each quarter set of trials (50 trials), with a further option to take another break.

3.2.3. Data management and analysis

Three-dimensional position data were processed using the same

Table 1Mean ($\pm$ SD) displacement (mm) at kinematic landmarks for each of the shaft and configuration conditions.

		Peak acceleration	Peak velocity	Peak negative acceleration	Movement end
Shaft	Tails-in	11.37 (3.33)	97.12 (12.80)	205.06 (23.44)	247.85 (2.89)
	Tails-mid	11.08 (3.14)	97.04 (14.66)	205.38 (21.14)	249.26 (2.92)
	Tails-combined	11.33 (3.74)	95.54 (18.64)	209.22 (22.67)	250.50 (3.51)
	Tails-out	11.07 (3.34)	97.76 (15.08)	213.86 (19.71)	251.07 (2.90)
No shaft	Tails-in	10.72 (3.23)	97.65 (15.90)	211.96 (17.23)	248.43 (2.41)
	Tails-mid	10.09 (3.50)	94.54 (14.47)	209.35 (17.37)	248.73 (2.97)
	Tails-combined	10.92 (3.33)	96.11 (13.86)	214.33 (18.59)	250.29 (2.41)
	Tails-out	100.27 (3.47)	98.19 (15.04)	214.36 (22.32)	251.48 (2.87)

filtering, differentiation, and onset/offset criteria as described in Experiment 1. Dependent measures included reaction time, movement time, constant error in both the primary and secondary axes, and displacement at kinematic landmarks (peak acceleration, peak velocity, peak negative acceleration, and movement end). With regard to the measures of spatial location; that is, constant error (CE) and kinematic landmarks, we extracted the position from both the primary (y-axis) (negative [-] CE_y value indicates an undershoot) and secondary (x-axis) (negative [-] CE_x value indicates left-of-target vertex) axes of movement.

Owing to a suspected error in the nominal display resolution, the last 9 of the 15 participants were presented with a different set of target amplitudes that were ~20% smaller than the original or intended amplitudes.¹ In a similar vein to Experiment 1, the data that solely comprised of the shorter amplitude (100 trials) were considered for subsequent inferential statistical analysis. Any trials with a reaction time <100 ms, movement time <100 ms or >1000 ms, and/or movement amplitude <50% of the target amplitude were removed prior to the analysis (1.41% trials). The analysis of reaction time, movement time and constant error (CE_y, CE_x) involved a two-way repeated-measures ANOVA comprising of shaft (shaft, no shaft) and configuration (tails-in, tails-right, tails-left, tails-combined, tails-out). Any significant factorial interactions were decomposed using simple effect analyses, while significant effects with more than two means were decomposed using the Holm-Bonferroni post hoc procedure. Meanwhile, the displacement at kinematic landmarks (y- and x-axes) were analysed using MANOVA (Wilks' λ). If there was a significant effect, then follow-up univariate ANOVAs were conducted with a Holm-Bonferroni adjustment.

3.3. Results and discussion

For reaction time, there were no significant main, nor interaction effects ($F_s = .46$ – 1.13 , $p_s = .34$ – $.56$, $\eta_p^2 = .03$ – $.08$) (*grand M* [$\pm$ SD] = 247 ms [$\pm$ 54]). Likewise, for movement time, there were significant no main, nor interaction effects ($F_s = .66$ – 1.68 , $p_s = .17$ – $.62$, $\eta_p^2 = .05$ – $.11$) (*grand M* [$\pm$ SD] = 500 ms [$\pm$ 84]). Therefore, any effects of the configuration on subsequent measures could not be confounded by systematic differences in movement preparation and/or overall movement duration, respectively.²

For CE_y, there was a significant main effect of shaft ($F[1,14] = 5.11$, $p = .04$, $\eta_p^2 = .27$), indicating that the limb movement was terminated shorter of the target for the shaft compared to no shaft. There was also a significant main effect of configuration ($F[4,56] = 7.58$, $p < .001$, $\eta_p^2 = .35$) (Fig. 4A).³ Subsequent post hoc analysis revealed that the limb

movement was terminated significantly shorter for tails-in ($p < .0063$), tails-right ($p < .0050$), tails-left ($p < .0071$), and tails-combined ($p < .0056$) compared to tails-out, although there were no further significant pairwise differences ($p_s > .05$). There was no significant interaction between shaft and configuration ($F[4,56] = .89$, $p = .40$, $\eta_p^2 = .06$).

For CE_x, there was no significant main effect of shaft ($F[1,14] = .01$, $p = .94$, $\eta_p^2 = .00$), although there was a significant main effect of configuration ($F[4,56] = 4.16$, $p = .02$, $\eta_p^2 = .23$) (Fig. 4B). Subsequent post hoc analysis revealed that the further rightward direction for tails-right reached significance when compared to tails-in ($p < .0050$), but only approached significance when compared to tails-combined ($p = .006$ [$>.0063$]), tails-out ($p = .059$ [$>.0071$]) and tails-left ($p = .067$ [$>.0083$]). In addition, there was a significantly more rightward direction for tails-out compared to tails-in ($p < .0056$). There was no significant interaction between shaft and configuration ($F[4,56] = 1.02$, $p = .40$, $\eta_p^2 = .07$).

For displacement at kinematic landmarks in the y-axis, the multivariate analysis revealed no significant main effect of shaft ($\Lambda = .80$, $F[4,11] = .69$, $p = .61$, $\eta_p^2 = .20$), although there was a significant main effect of configuration ($\Lambda = .55$, $F[16,163] = 2.19$, $p = .007$, $\eta_p^2 = .14$) (Table 2). Meanwhile, there was no significant interaction between shaft and configuration ($\Lambda = .77$, $F[16,163] = .89$, $p = .59$, $\eta_p^2 = .06$). Further univariate analysis at each level of kinematic landmark indicated no significant main effect of configuration at peak acceleration ($F[4,56] = .53$, $p = .72$ [$>.05$], $\eta_p^2 = .04$), peak velocity ($F[4,56] = 1.66$, $p = .17$ [$>.017$], $\eta_p^2 = .11$) and peak negative acceleration ($F[4,56] = .64$, $p = .64$ [$>.025$], $\eta_p^2 = .04$), although there was a significant main effect of configuration at movement end ($F[4,56] = 6.24$, $p < .001$ [$<.013$], $\eta_p^2 = .31$). Subsequent post hoc analysis revealed a significantly shorter displacement for tails-in ($p < .0063$), tails-right ($p < .0056$), and tails-combined ($p < .0050$) compared to tails-out, while the shorter displacement for tails-left compared to tails-out approached significance ($p = .0081$ [$>.0071$]). There were no further significant pairwise differences ($p_s > .05$).

For displacement at kinematic landmarks in the x-axis, the multivariate analysis revealed no significant main effect of shaft ($\Lambda = .77$, $F[4,11] = .84$, $p = .61$, $\eta_p^2 = .24$), although there was a significant main effect of configuration ($\Lambda = .47$, $F[16,163] = 2.82$, $p < .001$, $\eta_p^2 = .17$) (Table 3). Meanwhile, there was no significant interaction between shaft and configuration ($\Lambda = .78$, $F[16,163] = .86$, $p = .62$, $\eta_p^2 = .06$). Further univariate analysis at each level of kinematic landmark indicated no significant main effect of configuration at peak acceleration ($F[4,56] = .95$, $p = .43$ [$>.05$], $\eta_p^2 = .06$) and peak negative acceleration ($F[4,56] = 1.34$, $p = .27$ [$>.025$], $\eta_p^2 = .09$). However, there was a significant main effect of configuration at peak velocity ($F[4,56] = 4.84$, $p = .002$ [$<.013$], $\eta_p^2 = .26$) and movement end ($F[4,56] = 4.15$, $p = .005$ [$<.017$], $\eta_p^2 = .23$). Subsequent post hoc analysis at peak velocity revealed a significantly more rightward displacement for tails-right compared to tails-left ($p < .0050$), although there were no other significant pairwise differences ($p_s > .0056$). Meanwhile, at movement end, there was a significantly more rightward displacement for tails-right compared to tails-in ($p < .0050$), although there were no other significant pairwise differences ($p_s > .0056$).

² All significant effects ($p_s < .05$) from the main inferential statistical analysis of the original (unconverted) values were successfully replicated for the analysis of z-scores. What's more, there were no additional significant effects highlighted from the analysis of z-scores ($p_s > .05$).

³ Using G*Power software (v. 3.1.9.4) (Faul et al., 2007), we conducted a posteriori power analysis pertaining to our main hypothesized effects in endpoint bias (CE_y). For both experiments, the statistical power achieved was $1 - \beta \geq 1.00$, which considerably exceeds the recommended $1 - \beta \geq .80$ (Cohen, 1988).

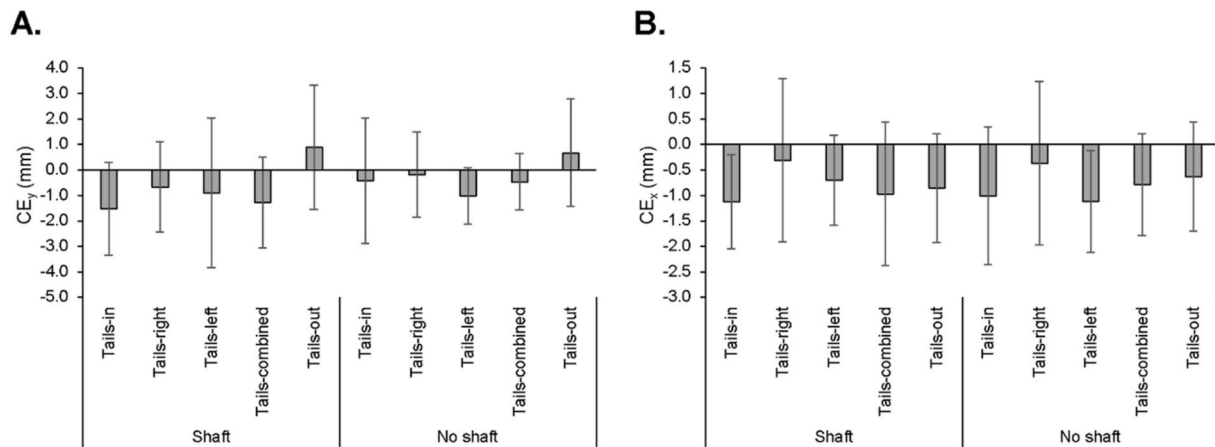


Fig. 4. Mean CE_y (A) and CE_x (B) as a function of shaft and configuration (error bars represent the standard deviation).

Table 2

Mean ($\pm$ SD) displacement (mm) at kinematic landmarks in the y-axis for each of the shaft and configuration conditions.

		Peak acceleration	Peak velocity	Peak negative acceleration	Movement end
Shaft	Tails-in	10.72 (3.30)	87.60 (16.03)	185.36 (23.27)	220.34 (25.53)
	Tails-right	10.62 (3.49)	87.67 (14.04)	187.74 (18.63)	221.17 (25.10)
	Tails-left	10.98 (3.79)	88.12 (15.87)	187.56 (21.84)	221.07 (25.88)
	Tails-combined	11.00 (4.13)	89.10 (14.32)	189.51 (16.94)	220.68 (25.28)
	Tails-out	10.65 (4.02)	89.40 (14.15)	185.73 (18.74)	223.06 (25.14)
No shaft	Tails-in	10.60 (3.59)	88.63 (15.62)	187.17 (17.39)	221.42 (25.99)
	Tails-right	11.18 (3.20)	85.17 (16.58)	189.29 (15.79)	221.51 (25.09)
	Tails-left	10.98 (3.33)	87.70 (13.20)	186.70 (19.50)	220.98 (24.18)
	Tails-combined	11.16 (3.86)	87.87 (15.59)	186.83 (21.80)	221.28 (24.99)
	Tails-out	11.00 (4.09)	88.82 (15.21)	189.93 (19.16)	222.38 (24.84)

Table 3

Mean ($\pm$ SD) displacement (mm) at kinematic landmarks in the x-axis for each of the shaft and configuration conditions.

		Peak acceleration	Peak velocity	Peak negative acceleration	Movement end
Shaft	Tails-in	-0.60 (1.11)	1.08 (3.79)	2.26 (2.74)	-0.33 (1.58)
	Tails-right	-0.51 (.90)	2.09 (3.93)	3.47 (3.68)	0.35 (1.92)
	Tails-left	-0.56 (1.24)	0.71 (3.67)	2.74 (3.27)	-0.07 (1.91)
	Tails-combined	-0.60 (1.01)	1.21 (4.07)	2.53 (3.45)	-0.14 (1.86)
	Tails-out	-0.61 (.94)	1.15 (3.76)	2.53 (2.36)	-0.11 (1.54)
No shaft	Tails-in	-0.61 (.95)	1.14 (3.75)	2.92 (3.58)	-0.33 (1.90)
	Tails-right	-0.41 (.83)	1.96 (3.23)	2.99 (3.34)	0.27 (1.99)
	Tails-left	-0.70 (1.02)	0.08 (4.20)	2.64 (3.83)	-0.52 (1.45)
	Tails-combined	-0.62 (1.04)	0.81 (4.09)	2.20 (3.56)	0.06 (1.64)
	Tails-out	-0.42 (.86)	1.29 (4.07)	2.59 (3.30)	0.27 (1.73)

Broadly speaking, the present study corroborates the findings and suggestions from Experiment 1. That is, there was a longer movement amplitude for the tails-out compared to the remaining other conditions, while there was also a more rightward shift for the tails-right. What's more, these effects unfolded independent of any influence of shaft. Thus, the present findings would categorically refute the role of the Müller-Lyer illusion in action; namely, there appears to be a limited influence of the allocentric cues alluding to a misperception in the target amplitude (e.g., Gentilucci et al., 1997; see also, Yan and Hondzinski, 2021). Instead, the findings may be alternatively explained by the perceived position in space according to the orientation of the tails (e.g., Mack et al., 1985; Glazebrook et al., 2005).

Further inspection of the movement kinematics as a proxy for planning and control revealed that while there was some indication of a rightward shift as early as peak velocity, the aforementioned effects mostly unfolded at the end of the movement. This follows the suggestion that any delayed online movement adjustments with a view to closing the gap between the limb and target locations may be more susceptible

to the target surround (Elliott et al., 2010, 2017; see also, Roberts et al., 2021).

4. General discussion

The Müller-Lyer illusion is one of a number of perceptual illusions that have been adapted to highlight a potential dissociation between the visual neural pathways for perception and action (Milner and Goodale, 1995). However, subsequent empirical observations have alternatively indicated how a perceptual bias following an illusion configuration may at least partially manifest within action. This has led to either an entirely opposing view of how perception and action share the same visual input (Franz, 2001; Bruno and Franz, 2009), and more nuanced proposals of how illusions separately guide planning and control processes (Glover and Dixon, 2001, 2002), or early and late phases of movement (Mendoza et al., 2005; Elliott et al., 2017). Along these lines, it is possible that the influence of illusions on perception and action may seemingly differ only because of their unique set of task constraints (see

Smeets and Brenner, 2001; Smeets et al., 2002).

With this in mind, the present study aimed to examine the precise configural properties comprising the Müller-Lyer illusion that are responsible for an influence on action. Hence, we had participants make aiming movements toward the vertex of conjoined tails that featured either a shaft and no shaft. If movements are the product of a misperceived length from allocentric coding, then we would assume only a shorter amplitude for the tails-in, and a longer amplitude for the tails-out, but only when the shaft was present. Alternatively, if movements are contingent upon the perceived endpoint position; that is, the convergence at the tail-ends, then we would assume movement endpoints to be shifted in a direction of the tails independent of the shaft. The evidence across both experiments appeared to be strongly in favour of the latter.

Consistent with the present findings, it has been previously shown that illusion-induced biases are evident only when making comparisons to effectively equate length, although they become nullified when making judgements around isolated positions in space (Mack et al., 1985; Post and Welch, 1996). In a similar vein, the biases inflicted by tail-ends have been shown to equally unfold for the Müller-Lyer ($>-<$) and Judd ($<-<$) configurations despite them having separate effects on the perception of length and position, respectively (Glazebrook et al., 2005). Taken together, it appears the configural properties that steer movement outcomes are not a product of misperceived length. Instead, it is perhaps more likely attributed to the perceived ‘centroid’ that falls within the same direction of the tails, and thus would be comparatively short and long for the tails-in and tails-out configurations, respectively (Coren, 1986; Searleman et al., 2005; Bulatov et al., 2009, 2011, 2022). Here, Gestalt-based grouping principles assume the closure of adjacent stimulus features, which would have the effect of contracting and expanding areas in space that are occupied by the tails-in and tails-out configurations, respectively (Coren and Girgus, 1980).

Furthermore, it appears the influence of the configuration was largely found toward the end at the termination of the movement. This finding concurs with previous evidence of the Müller-Lyer configuration influencing movement displacement, but only within the events following peak velocity (Heath et al., 2007; for similar findings with the Ebbinghaus/Titchener circles illusion [relating to perceived target size] on time, see Handlovsky et al., 2004). Meanwhile, the influence of the Müller-Lyer configuration on movement endpoints can also be found even when this configuration is presented later following movement onset (Mendoza et al., 2006; Grierson and Elliott, 2009a; Roberts et al., 2013). Taken together, the evidence suggests that the configural properties of the target hold most influence toward the end of the movement, presumably when the remaining distance between the limb and target positions is slowly decreased online (Elliott et al., 2010, 2017; see also Mendoza et al., 2005). However, rather than it being related to dissociated perception and action processes, we suggest that movement endpoint likely manifests from a culmination of visual inputs that are received throughout the entire movement. In other words, the configural properties during the early movement preparation can also influence the later movement toward the end (Mendoza et al., 2006; Blinch et al., 2012). While this explanation clearly opposes the planning-control model (Glover and Dixon, 2001, 2002), it is possible that such discrepancies may be reasonably attributed to a mere subtle variation in study paradigms and related processes across the literature (e.g., grasping vs. pointing, open-vs. closed-loop, etc; for a similar logic, see Smeets et al., 2019; Roberts et al., 2021).

Upon review, we sought to examine the source of the bias within aiming that is typically inflicted by Müller-Lyer configurations. Broadly speaking, this was done by manipulating a combination of the presence of the shaft and orientation of the tails to effectively control for the illusion and any related misperception in length. We showed that aiming movements were steered independently of the shaft, and more toward the direction of the tails. These findings refute the role of allocentric reference codes, and with it, the logic behind the separate contributions

from distinct visual neural pathways for perception and action (Milner and Goodale, 1995; Glover and Dixon, 2001, 2002). Instead, we suggest that the influence was primarily related to the tails themselves, where they would be grouped together to effectively “fence-in” the perceived ‘centroid’. In this regard, the findings are perhaps more aligned with the suggestion of a distinction between perception and action solely based on separate sets of task constraints (Smeets and Brenner, 2001; Smeets et al., 2002). Moreover, these findings were primarily isolated to the end of the movement, and thus support the view of configurations manifesting during late limb-target control (Elliott et al., 2010, 2017).

CRediT authorship contribution statement

J.A.M. Cappelletto: Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.W. Roberts:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **J.L. Lyons:** Writing – review & editing, Supervision, Conceptualization.

Data availability

Data will be made available upon reasonable request to one of the listed authors.

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Declaration of competing interests

The authors declare that they have no conflicts of interest.

Key resources table

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
E-prime	Psychology Software Tools	
Matlab	MathWorks	

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