Revisiting the color-motion asynchrony

Jianrui Huang*
Beijing Key Laboratory of Behavior and Mental Health,
School of Psychological and Cognitive Sciences,
Peking University, Beijing, China

Zhongbin Su*
Shanghai Key Laboratory of Psychotic Disorders,
Shanghai Mental Health Center, Shanghai Jiao Tong
University School of Medicine, Shanghai, China
Institute of Psychology and Behavioral Science,
Shanghai Jiao Tong University, Shanghai, China

Xiaolin Zhou
Beijing Key Laboratory of Behavior and Mental Health,
School of Psychological and Cognitive Sciences,
Peking University, Beijing, China
Shanghai Key Laboratory of Mental Health and
Psychological Crisis Intervention, School of Psychology
and Cognitive Science, East China Normal University,
Shanghai, China
PKU-IDG/McGovern Institute for Brain Research,
Peking University, Beijing, China

Color-motion asynchrony (CMA) refers to an illusion in which we perceive a change in color earlier than a change in motion direction when the two changes occur simultaneously. This phenomenon may indicate that color is processed earlier than motion in the visual system. However, the very existence of CMA is under question owing to contradictory findings and methodological deficits in previous studies. Here, we used both the motion and color correspondence tasks (experiment 1) and the temporal order judgment (TOJ) task (experiment 2) to re-examine CMA. Colored dots moved in one direction and changed their color/direction at some time, whereas the relative timing between color and direction changes varied across trials. In the correspondence task, participants reported which direction/color of dots with a particular color/direction lasted longer, the one before or after the change? In the TOJ task, participants reported whether the change in color or the change in motion direction occurred earlier. Results indicated that participants perceived the change in color earlier than the change in motion direction in either the motion or color correspondence task, with a stronger asynchrony in the former. In the TOJ task, although participants showed no difference in psychophysical measures, they responded faster when the change in color occurred before (versus after) the change in direction. Drift-diffusion modeling (DDM) revealed a lower decision threshold when the change in color occurred before (versus after) the change in direction, indicating less cautiousness was excised in judgment when the color changed earlier. These results confirmed the veracity of CMA in different tasks and point to the viability of analyzing response times in traditional psychophysical studies.

Introduction

Color-motion asynchrony (CMA), first reported and named by Moutoussis and Zeki (1997), refers to an illusion in which we perceive a change in color approximately 80 ms earlier than a change in motion direction when a stimulus repeatedly and rapidly changes color (e.g. between red and green) and motion direction (e.g. between upward and downward). This striking phenomenon may indicate that in addition to being processed separately in geographically distinct parts of the visual brain (Livingstone & Hubel, 1987; Zeki, 1979), color and motion are also perceived with distinct temporal latencies. CMA has been studied quite extensively in the last 25 years, typically with the color (or motion) correspondence task and temporal order judgment task. However, the veracity of CMA is constantly under question owing to contradictory

Citation: Huang, J., Su, Z., & Zhou, X. (2023). Revisiting the color-motion asynchrony. *Journal of Vision*, *23*(1):6, 1–14, https://doi.org/10.1167/jov.23.1.6.

https://doi.org/10.1167/jov.23.1.6 Received August 18, 2022; published January 10, 2023 ISSN 1534-7362

findings and some methodological deficits in studies using these tasks.

In the color correspondence task, stimuli (e.g. dots) repeatedly and rapidly change color and motion direction with the same frequency in a given time window but with different phases (e.g. Holcombe & Cavanagh, 2008; Moutoussis & Zeki, 1997; Nishida & Johnston, 2002). At any time point, all the stimuli are either red or green and are moving in one direction. That is, all the stimuli can be considered as a single object with two dimensions or features, color, and motion direction. Participants are asked to pair the appropriate color to each direction of motion (i.e. color correspondence) or to pair the appropriate direction to each color (i.e. motion correspondence). Specifically, they are asked to press one key if the predominant color (i.e. the color whose aggregated duration in a trial is longer) of the upward motion is green and the predominant color of the downward motion is red, and another key if a reverse pattern is perceived. The initial study using this paradigm (Moutoussis & Zeki, 1997) showed that when a change in motion direction and a change in color occurred simultaneously, participants mostly reported that the color of the upward motion was green and that of downward motion was red, but not at 100% response rate. Only when the change in direction occurred approximately 80 ms earlier than the change in color, would participants report that "the color of the upward motion was green and that of downward motion red" at nearly 100% rate; that is, the change in color and the change in motion direction appeared to occur simultaneously in this situation. Subsequent studies simplified the paradigm with a single change of color and a single change of motion direction in a trial (Ayhan, Kurtcan, & Thorpe, 2020; Linares & Lopez-Moliner, 2006; Self, 2014). In these studies, the change in color always occurred first and the change in motion direction appeared later. Participants were asked to report which motion direction of the stimuli with the second color (i.e. the color after the change in color) lasted longer, the direction before or after the change in direction. That is, these studies used a motion correspondence task. Results from the three studies showed that participants perceived the latter duration as shorter than the former, implying that if the change in color and the change in motion direction occur at the same time, participants would perceive the change in color earlier. Note, these studies did not utilize the color correspondence task.

As Table 1 summarizes, past studies using either the repeated-change or single-change paradigm produced mixed findings. Although some studies confirmed the existence of CMA (e.g. Ayhan et al., 2020; Holcombe & Cavanagh, 2008; Moutoussis & Zeki, 1997), other studies observed either a null effect (e.g. Nishida & Johnston, 2002) or even a reversed pattern (e.g. Enns & Oriet, 2004). Several design parameters appear to influence the pattern of effects, including the time interval between repeated changes (Nishida & Johnston, 2002), the angle of direction change (e.g. Amano, Johnston, & Nishida, 2007; Arnold & Clifford, 2002), and the coherence of motion direction (McIntyre & Arnold, 2018).

These studies may be susceptible to a number of criticisms. For example, it is argued that the perceptual asynchrony is a natural consequence of redirecting attention from a "defining" attribute (e.g. motion direction) to a "report" attribute (e.g. color) and reversing defining and report attributes in the correspondence task could reverse CMA (Enns & Oriet, 2004). When participants attended to color first and the motion direction changed halfway in the (second) color period, they were more likely to report that the first motion direction lasted longer than the second direction (indicating "color leading motion"). In contrast, when participants attended to motion first and the color changed halfway in the motion period, participants tended to report that the first color lasted longer than the second one (indicating "motion leading color"). That is, the so-called CMA might result from redirecting attention from one feature to another in the previous studies. To claim a general primacy of color change processing, it is important to conduct both color and motion correspondence tasks. It is clear from Table 1 that most studies included only one task. Moreover, in the studies using the single change paradigm (Ayhan et al., 2020; Linares & Lopez-Moliner, 2006; Self, 2014), ideally in experimental setup the number of trials having a longer duration between color change and motion direction change shorter than the duration after motion direction change should be equal to the number of trials having a longer duration in the latter than in the former; that is, the distribution of different types of trials should be symmetric, centering around the second (motion direction) change. However, in all the three studies using the single change paradigm, about 70% trials had a longer duration after a change in motion direction, creating a priori response bias for the latter. Furthermore, it is obvious from Table 1 that most studies had a very small sample size and used a between-subject design if the studies did use both the correspondence tasks (e.g. Amano et al., 2007; Arnold, Clifford, & Wenderoth, 2001; Ayhan et al., 2020), precluding the possibility of drawing strong conclusions based on their findings (Moutoussis, 2012).

In a temporal order judgment (TOJ) task, the stimulus could be the same as in the single change correspondence task, but participants are asked to report whether the change in color occurs before or after the change in motion direction (e.g. Ayhan et al., 2020; Linares & Lopez-Moliner, 2006; Nishida & Johnston, 2002; Self, 2014; Viviani & Aymoz, 2001). This task seems to be a more direct way to compare the perceptual latency of a change in color and a

Authors, year	Correspondence task	Stimulus	Sample size	Results
Amano et al. (2007)	Color	Repeated	3	Color < motion CMA was reduced as the angle of direction change reduced
Arnold (2005)	Color	Repeated	2	Color < motion
	Motion correspondence	Repeated	2	color < motion
Arnold and Clifford (2002)	Color	Repeated	2	Color < motion CMA was reduced as the angle of direction change reduced
Ayhan et al. (2020)	Motion	Single	5	Color < motion
Bedell et al. (2003)	Color	Repeated	4	Color < motion CMA was reduced as the angle of direction change reduced
Clifford et al. (2004)	Color	Repeated	5	Color < motion
Clifford, Arnold, and Pearson (2003)	Color	Repeated	3	Color < motion (orientation)
	Orientation	Repeated	3	CMA was stronger in orientation correspondence task
Enns and Oriet (2004)	Color	Repeated	Unknown	Color > motion
	Motion	Repeated	Unknown	Color < motion
Holcombe and Cavanagh (2008)	Color	Repeated	5	Color < motion
		Repeated	5	Color < motion
	Motion	Repeated	5	Color < motion
		Repeated	5	Color < motion
Holcombe and Cavanagh (2008)	Color	Repeated	10	Color < motion, CMA reduced as the coherence of motion reduced
		Repeated	10	CMA was reduced as the coherence of motion was reduced.
	Motion	Repeated	10	Color < motion, CMA reduced as the coherence of motion reduced
	Motion correspondence	Repeated	10	
Zeki (1997)	Color	Repeated	9	Color < motion
Moutoussis and Zeki (1997)	Color	Repeated	4	Color < motion
Nishida and Johnston (2002)	Color	Repeated	3	Color < motion (change interval > 700 ms) Color = motion (change interval < 700 ms)
Nishida and Johnston (2002)	Color	Single	3	Color = motion
Linares and Lopez-Moliner (2006)	Motion	Single	3	Color < motion
Self (2014)	Motion	Single	4	Color < motion

Table 1. Results of the color and motion correspondence tasks in different studies. Note: “color < motion” means participants perceive color change earlier than motion direction change; “color > motion” means participants perceive color change later than motion direction change; “color = motion” means participants perceive color change as fast as motion direction change. In studies with single-change design, PSE was used as the index for CMA; in studies with repeated-change design, other indices such as the timing of best response were used for CMA.

change in direction. However, as Table 2 shows, studies appealing to this paradigm also produced inconsistent results. Although some studies showed that participants perceived a change in color change earlier than a change in motion direction (Ayhan et al., 2020; Self, 2014; Viviani & Aymoz, 2001), other studies found that participants could precisely perceive the timing of color change and direction change, showing no CMA

Authors, year	Task demanding	Sample size	Results
Ayhan et al. (2020)	Reported whether the direction change had taken place before or after the change in color	5	Color < motion
Aymoz and Viviani (2004)	Reported whether a change in color occurred before or after the onset of motion	20	Color < motion
Bedell et al. (2003)	Reported whether a change in color occurred before or after a change in motion	4	Color = motion
Clifford, Arnold, and Pearson (2003)	Reported whether changes in color and orientation were simultaneous	3	Color = motion
Gauch and Kerzel (2008)	Reported whether object changed color before (vs. after) it started to move	14	Color > motion
Linares and Lopez-Moliner (2006)	Reported whether the direction change occurred before or after the color change	3	Color = motion
Nishida and Johnston (2002)	Reported which (color or motion) changed occurred first	1	Color = motion
Self (2014)	Reported whether the motion or the color changed first	10	Color < motion
Viviani and Aymoz (2001)	Reported whether a change in color occurred before or after the onset of motion	20	Color < motion

Table 2. Results of the temporal order judgment task in different studies. Note: "color < motion" means participants perceived color change earlier than motion direction change; "color > motion" means participants perceived color change later than motion direction change; "color = motion" means participants perceived color change as fast as motion direction change. In this task, most studies used single-changed stimuli except Clifford, Arnold, and Pearson (2003).

(Bedell, Chung, Ogmen, & Patel, 2003; Clifford, Arnold, & Pearson, 2003; Linares & Lopez-Moliner, 2006; Nishida & Johnston, 2002).

The discrepancy between the findings of these studies using the TOJ task might be partly explained by differences in stimulus parameters, such as retinal location (Bedell et al., 2003; Self, 2014; Viviani & Aymoz, 2001) and stimulus quantity (Ayhan et al., 2020; Linares & Lopez-Moliner, 2006). The small sample size is another possible deficit that renders the studies missing CMA (Self, 2014). Importantly, the use of traditional psychophysical measures, such as point of subjective equality (PSE; also called point of subjective simultaneity [PSS]) could reduce the task's sensitivity in detecting subtle effects in TOJ. In line with most other psychophysical studies, the TOJ studies on CMA typically used PSE as an index of the sensitivity of participants in perceiving a change of color and a change in motion direction. However, the time at which the participants perceive the occurrence of the two changes and decide which change happens first could be more directly measured by response time (RT) in TOJ. Mathematical modeling, such as drift-diffusion modeling (DDM; Fudenberg, Newey, Strack, & Strzalecki, 2020; Ratcliff & McKoon, 2008; Wiecki, Sofer, & Frank, 2013), allows us to differentiate to some extent cognitive processes involved in perceiving and deciding color and motion direction changes.

Given the contradictory findings and design deficits in previous studies on CMA, the extent to which CMA exists in different tasks is a question that needs to be reexamined and settled. Here, in Experiment 1, we utilized a within-subject design in which a relatively large number of participants completed the single-change version of both the motion and color correspondence tasks. In the color correspondence task, the motion direction of the dots changed first and the color of the stimuli changed some time later. Participants were asked to report the predominant color of the stimuli (i.e. whether the color of the dots before or after a color change lasted longer) for the stimuli of the second direction. In the motion correspondence task, the color of the dots changed first and the motion direction of the stimuli changed some time later. Participants were asked to report the predominant direction (i.e. the longer-lasting direction) of the stimuli with the second color. If the redirection of attention from motion direction to color in the color correspondence task or from color to motion direction in the motion correspondence plays a role in CMA, we would expect to observe different patterns of effects in the two tasks, possibly a smaller or even reversed color-motion asynchrony in the color (versus motion) correspondence task.

In Experiment 2 with the TOJ task, we again used the single-change version of stimuli and manipulated the time interval between the change color and the change in motion direction, but asked participants to decide whether the change in color or the change in direction occurred earlier by pressing one of the two response keys. Apart from the typical psychophysical measure (i.e. PSE), we recorded participants' response times. We reasoned that if the change in color is indeed perceived earlier than the change in motion direction, participants should respond faster in the condition in which the change in color occurs before (versus after) the change in direction.

Experiment 1

Methods

Participants

Thirty-one undergraduate and graduate students took part in Experiment 1. Three of them failed to meet our criteria for data quality (see Data analyses below) and were therefore excluded. The remaining 28 participants, including 10 male participants, had an age range of 19 to 28 years (mean age = 21.89 years, SD = 2.28 years). They were all right-handed, had normal color vision, and normal or corrected-to-normal visual acuity, and reported no history of cognitive and psychiatric disorders. Participants received monetary compensation for their participation. Informed consent was obtained from each participant prior to the commencement of the experiment. The study (including Experiments 1 and 2) was approved by the Committee for Protecting Human and Animal Subjects, School of Psychological and Cognitive Sciences, Peking University, and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Procedures and materials

Participants were tested individually in a quiet and dim cubicle. They were first given instructions concerning the tasks and procedures of the study and then performed the motion correspondence task and color correspondence task, with the order of the two tasks counter-balanced across participants. The experiment took approximately 40 minutes to complete.

Visual stimuli were presented on a 27-inch LCD monitor (refresh rate = 100 Hz, resolution = 1920 × 1080) connected to a DELL computer. Stimulus presentation and participants' response recording were controlled by Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) with MATLAB. Participants viewed the monitor from a distance of approximately 57 cm, and the head position was stabilized with a chinrest.

The motion correspondence task

Participants were asked to make judgments about the predominant direction of motion when the moving dots were in the second color (i.e. after the color had changed). The change in color change always occurred before the change in motion direction, at the mid-point of the entire duration of stimulus presentation (i.e. 400 ms after the onset of stimuli; see Figure 1) in a trial. The relative timing between the two changes varied from trial to trial. We assigned a relative timing of zero at the mid-point of the second color (i.e. 600 ms after onset) and assigned negative (−150, −100, and −50) or positive values (150, 100, and 50) to the time point of direction change occurring before or after the zero point (see Linares & Lopez-Moliner, 2006). Thus, relative to the mid-point of the second color, the timings of motion direction changes (and the number of trials) were symmetric, avoiding the potential response biases mentioned earlier.

Each participant performed two different sessions: one in which the second color was red (luminance = 20 cd/m^2; and chromaticity = 0.68 and 0.31) and another in which the second color was green (luminance = 20 cd/m^2; and chromaticity = 0.25 and 0.67). The order of the two sessions was counter-balanced across participants. In each session, the stimuli could change direction either from upward to downward or from downward to upward. During a session, each relative timing was sampled 12 times, giving 168 (12 × 7 [relative timing] × 2 [session]) trials in the whole motion correspondence task. Trials of different conditions were randomly mixed and presented. Before the formal experiment, participants completed a 20-trial practice block to get familiar with the task.

During each trial, a fixation cross (0.6 degrees × 0.6 degrees at 20 cd/ m^2) was presented at the center of the screen to guide participants' gaze in a dark room. Initially, 200 dots (0.3 degrees × 0.3 degrees each) of the same color (e.g. green) moved in the same direction (e.g. downward). The color of the dots changed at the mid-point of the presentation, with both colors lasting 400 ms. When the stimuli disappeared, participants were prompted to report the predominant direction of the motion of the dots in the second color by pressing an appropriate key (the left or right arrow of the keyboard, counter-balanced across participants). The next trial began 500 to 1500 ms after the participant's response.

The color correspondence task

The overall task settings and procedures of the color correspondence task were parallel to those of the motion correspondence task. As shown in Figure 2, the change in motion direction change always occurred earlier than the change in color, at the mid-point of

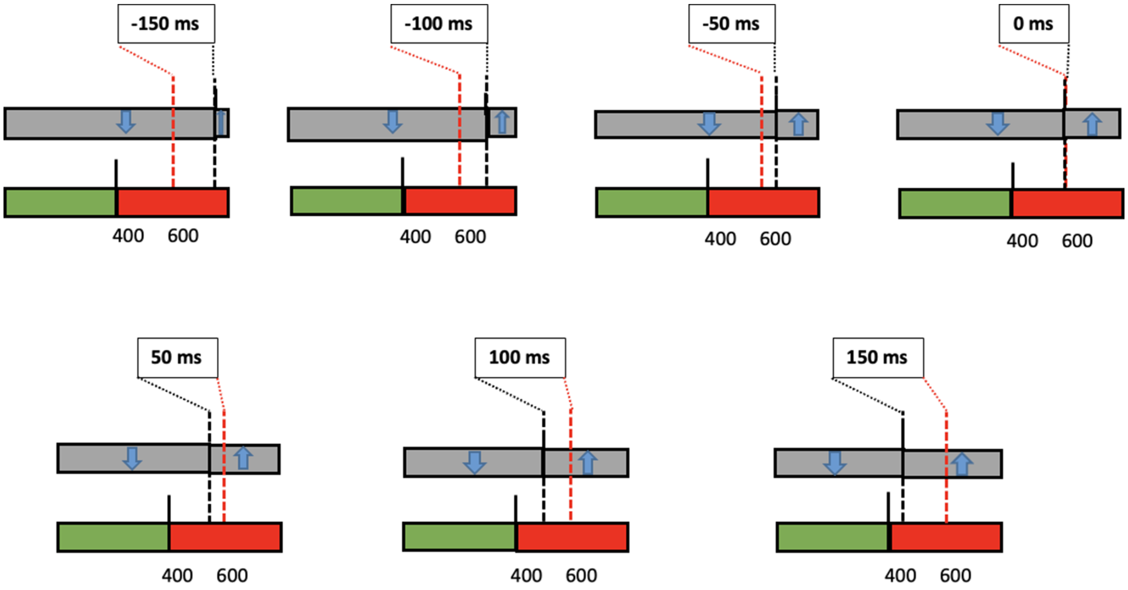

Figure 1. Temporal profiles of the changes in motion direction and color of the stimuli in the motion correspondence task. The upper bar and lower bar portray a change in motion direction and a change in color respectively, with the broken black line in the upper bar denoting the time point of motion direction change and the solid line in the lower bar denoting the time point (i.e. 400 ms after onset) of the change in color. The red broken line indicates the mid-point of the duration of the second color (i.e. 600 ms after the onset). At any time point, all of the stimuli (i.e. dots) were moving either downwards or upwards, and were either green or red. Participants were asked to judge which duration is longer, the duration of the stimuli in the second color before the change in direction or the duration of the stimuli in the second color after the change in direction.

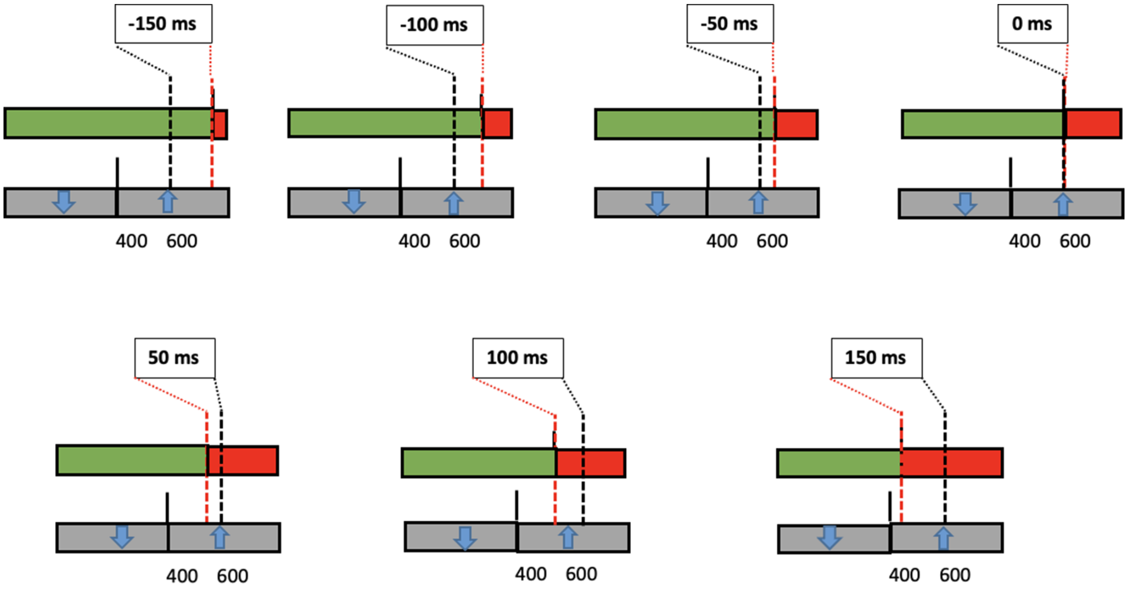

Figure 2. The temporal profiles of the changes in motion direction and color of the stimuli in the color correspondence task. The upper bar and lower bar portray the change in color and motion direction respectively, with the broken red line in the upper bar denoting the time point of the change in color and the solid line in the lower bar denoting the time point (i.e. 400 ms after onset) of the change in motion direction. The black broken line indicates the mid-point of the duration of the second color (i.e. 600 ms after the onset). At any time point, all of the stimuli (i.e. dots) were moving either downwards or upwards, and were either green or red. Participants were asked to judge which duration is longer, the duration of the stimuli in the second direction before the change in motion direction or the duration of the stimuli in the second direction after the change in motion direction.

motion (i.e. 400 ms after the onset of stimuli). The relative timing between the change in color and the mid-point of the second motion direction (i.e. 600 ms after onset of stimuli) had seven levels (−150, −100, −50, 0, 50, 100, and 150). Participants were asked to make judgments about the predominance of the colors after the motion direction was changed. Each participant performed two sessions, with the order of the session counter-balanced over participants. In one session the second (target) direction after the change in direction was upward, and in another session the second direction was downward.

Data analyses

The percentage of second direction (in the motion correspondence task) or second color (in the color correspondence task) reports was computed for each level of relative timing. The seven data points, one for each relative timing, were fitted into the psychometric curve using a logistic function (Treutwein & Strasburger, 1999) for each participant. The PSE was calculated by estimating the point of 50% reporting the second direction or the second color on the fitted curve. One sample *t*-tests on PSE versus 0 were conducted. The just noticeable difference (JND; i.e. the difference between two relative timings that participants were able to detect) was also calculated, which equaled to half of the difference between the 75% threshold and 25% threshold of the fitted curve.

Participants with PSE 2 steps (100 ms) below or over 0 (the relative timing at which participants would respond at a chance level for the two forced-choice judgment if CMA did not exist) were excluded from all the data analyses. Such participants had a strong perceptual bias toward either a change in motion direction change or a change in color direction. Participants with JND 2 steps (100 ms) over 0 were also excluded from data analyses because these participants were unable to perform the task well (i.e. the relative timing between color change and motion direction change was too short for them to complete the task). Overall, three participants were excluded, although including them does not change the pattern of effects.

In the case where a null hypothesis was accepted under a nonsignificant effect of the *t*-test, we calculated the Bayesian Factor, BF_{01} (Wagenmakers et al., 2018), using JASP (Wagenmakers et al., 2018, https://jasp-stats.org/) to quantify the extent to which the null hypothesis was supported.

Results and discussion

For the motion correspondence task (Figure 3, left panel), one sample *t*-test showed that the PSE was significantly larger than 0, mean = 48 ms, $t(27) = 9.38$, $p < 0.001$, *Cohen's D* = 1.77, indicating that when the change in motion direction occurs 48 ms earlier than the objective midpoint of the duration of the second color, participants would subjectively perceive the two durations of the second color (corresponding to dots moving in two different directions) as being equally long. Thus, the current task replicated the typical CMA in which the change in color is perceived earlier than the change in motion direction if these two changes happen objectively at the same time.

For the color correspondence task, a one sample *t*-test on PSE (vs. 0) also revealed a significant effect, mean = −28, $t(27) = -5.33$, $p < 0.0001$, *Cohen's D* =

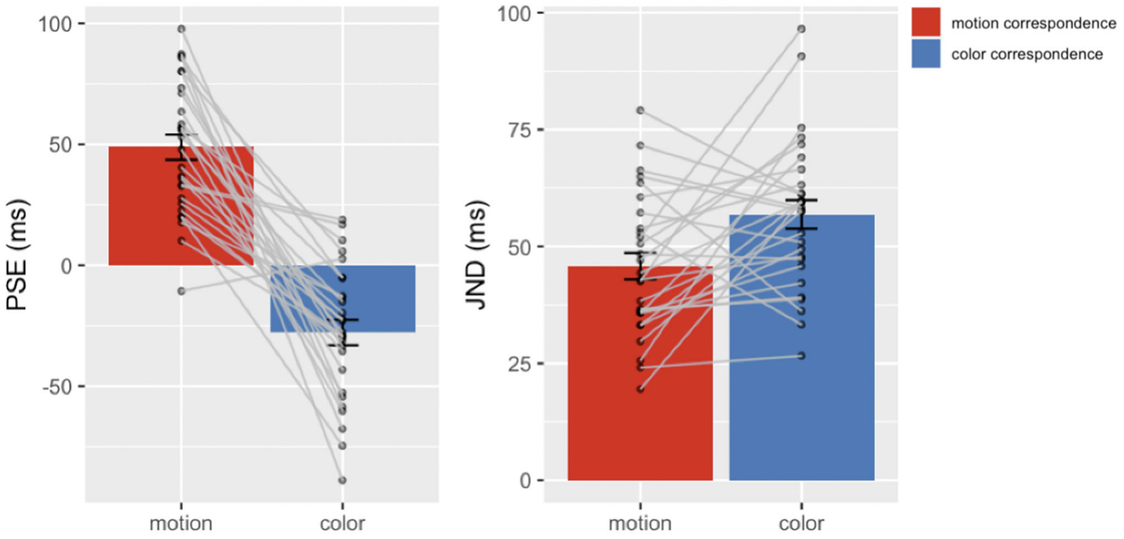

Figure 3. Results of the motion and color correspondence tasks in Experiment 1. Left panel: Results of PSE; Right panel: Results of JND. Error bars denote SEM. Dots and lines denote individual data.

-1.01, indicating that when the change in color change occurs 28 ms later than the midpoint of the second stage of motion, participants would perceive the durations of the second color before and after the change in motion direction as being equally long, a pattern consistent with CMA in the motion correspondence task.

A further comparison between the color-motion asynchrony in the two tasks was conducted, with the CMA of each participant in the color correspondence task defined as the opposite number of PSE. A paired-sample t-test revealed that CMA was stronger in the motion correspondence task than in the color correspondence task (48 vs. 28 ms), $t(27) = 3.48$, $p = 0.002$, $Cohen's\ D = 0.66$.

For JND (see Figure 3, right panel), paired-sample t-test revealed that the JND was smaller in the motion correspondence task (45 ± 15) than in the color correspondence task (56 ± 16), $t(27) = 2.85$, $p = 0.008$, $Cohen's\ D = 0.54$, indicating that the participants' sensitivity to the relative timing between the change in color and the change in motion direction was greater in the motion correspondence task than in the color correspondence task. In other words, the motion correspondence task was easier for participants to complete than the color correspondence task.

Experiment 2

In Experiment 2, participants were asked to report whether the motion direction or the color of moving dots changed first in a given trial. Thus, unlike Experiment 1, the change in color could occur before or after the change in motion direction. Experiment 2a was conducted with the typical psychophysical instructions for the participants (i.e. with no explicit time pressure on the participants' responses). Experiment 2b was essentially a replication of Experiment 2a except that participants were asked to respond as quickly and as accurately as possible.

Methods

Participants

Fifty-one undergraduate and graduate students took part in Experiment 2. Seven of them failed to meet our criteria for data quality and were therefore excluded (see Data analyses below). The remaining 44 participants, including 16 male participants, had an age range of 17 to 27 years (mean age = 21.16 years, SD = 2.43 years). Seventeen of them took part in Experiment 2a, and the remaining 27 participants took part in Experiment 2b. Informed consent was obtained from each participant prior to the commencement of the experiment.

Procedures and materials

For both Experiments 2a and 2b, the relative timing between the change in color and the change in motion direction had 7 levels: -210, -140, -70, 0, 70, 140, and 210 ms, with the negative values denoting an earlier change in color than change in motion direction. We used a larger step of 70 ms instead of the step of 50 ms used in Experiment 1 because our pilot experiment showed that this parameter would give a better estimation of task difficulty and goodness of fit of the psychophysical function. We assigned a relative timing of zero when the change in color and change in motion direction occurred simultaneously, and assigned negative (-210, -140, and -70) values when the change in color occurred before the change in motion direction or positive values (210, 140, and 70) when the change in color occurred after the change in motion direction. Each relative timing condition included 24 trials.

The first change of the stimuli, either the change in color or the change in motion direction, occurred 300 to 500 ms after the onset of the stimuli, and the stimuli disappeared 300 to 500 ms after the second change of the stimuli. The stimuli in a trial lasted from 600 ms to 1210 ms, varying over different trials. The remaining procedures were essentially the same as those in Experiment 1.

Data analyses

PSE was calculated in the same way as in Experiment 1. For RT analysis (only correct trials), we separated the relative timings between the change in motion direction and the change in color (excluding the 0 condition) into two categories: "color lead," with the change in color occurring before the change in motion direction; "motion lead," with the change in motion direction occurring before the change in color. If a participant's judgment on a particular trial was consistent with the physical timing of the stimuli, we defined it as a correct response. We further classified the relative timing conditions (excluding the 0 condition) based on task difficulty: easy (±210 ms), medium (±140 ms), and hard (±70 ms). Then, we conducted a two (lead condition: color lead versus motion lead) times three (task difficulty: easy, medium, and hard) repeated measures analysis of variance (ANOVA) on RTs.

The criteria for data quality of PSE/JND were the same as in Experiment 1. As a result, seven participants were excluded, although including them does not change the overall pattern of effects. Moreover, trials with RTs more than 2.5 standard deviations above or below each participant's mean were removed from the RT analysis (Experiment 2a: 3.09% of all the trials; and Experiment 2b: 2.95% of all the trials).

Hierarchical drift-diffusion model analysis

Behavioral data were fit with a hierarchical drift-diffusion model (HDDM) that has widely been used recently to decompose the decision making processes underpinning task performance (Fudenberg et al., 2020; Ratcliff & Childers, 2015; Ratcliff & McKoon, 2008; Ratcliff, Smith, Brown, & McKoon, 2016; Wiecki et al., 2013). DDM assumes that, in a speeded decision making task, people make decisions based on gradually accumulating evidence that is sampled from a noisy environment until a threshold is reached (e.g. Hu, Lan, Macrae, & Sui, 2020). With RT distributions of two alternative choices, the decision making process can be typically characterized by four estimated parameters within DDM (Ratcliff et al., 2016). Drift rate (v) estimates the rate of information acquisition, which is an index of task difficulty or stimulus quality (larger drift rate = faster information uptake). Threshold separation (a, also called boundary separation) represents the level of caution in decision making; increasing threshold separation results in fewer errors but at the cost of a slower response. A single starting value (z) represents an a priori bias or preference for one or the other response, and the parameter (t_0) represents all non-decisional processes (e.g. stimulus encoding and response execution).

In the current study, the HDDM analysis was conducted via a Python-based toolbox called HDDM (https://hddm.readthedocs.io/en/latest/; Wiecki et al., 2013). Instead of separately estimating parameters for each participant in the traditional DDM, HDDM estimates group and participant parameters simultaneously at different hierarchical levels by assuming that participant parameters are drawn from a group distribution. The Bayesian method is used to infer the posterior distribution of each parameter. Thus, the statistic results of parameter difference between conditions could be directly achieved through comparing the estimated posterior distributions. With the correct and incorrect RTs distributions, all model parameters were estimated using four Markov Chain Monte-Carlo (MCMC) chains of 10,000 samples, each with 2000 burn-in samples to allow for the chain to converge. The four chains were used to calculate the Gelman–Rubin convergence statistic for all model parameters. This statistic was close to 1 (<1.05), indicating that the 10,000 samples were sufficient for MCMC chains to converge (see Wiecki et al., 2013). Each HDDM parameter for each participant and each condition was modeled to be normally distributed centered around the group mean with group variance.

For better control of individual differences in overall performance, we used a within-subject model in which an intercept was used to capture overall performance in the "color lead" condition and the "motion lead" condition was expressed relative to this intercept. This within-subject model would explain large variance in the intercept but still allow the model to infer a non-zero effect of condition with high precision (see https://hddm.readthedocs.io/en/latest/tutorial_basic_hddm.html#within-subject-effects).

Results and discussion

For Experiment 2a, a one sample t-test revealed no significant difference between PSE (mean = −5 ms) and 0, $t(17) = -0.52$, $p = 0.61$, *Cohen's D* = −0.13. This null effect was confirmed by the $BF_{01} = 3.57$, suggesting that the null hypothesis was 3.75 times more likely to be true than the alternative hypothesis. For RTs of the correctly responded trials (Figure 4, upper panel) after removing the incorrect trials (3.09% of all the trials), a two (lead condition: color lead versus motion lead) times three (task difficulty: easy, medium, and hard) ANOVA revealed a significant main effect of difficulty, $F(2,32) = 17.79$, $p < 0.001$, ${\eta^2}_p = 0.53$, and a significant main effect of lead condition, $F(1,26) = 17.60$, $p < 0.001$, ${\eta^2}_p = 0.52$. The interaction between the two factors reached significance, $F(2,32) = 3.83$, $p = 0.03$, ${\eta^2}_p = 0.19$. Analyses of simple effects showed that, when the level of task difficulty was "easy," there was no significant difference between "color lead" and "motion lead," $t(16) = 1.57$, $p = 0.14$, *Cohen's D* = 0.34. When the level of difficulty was "medium," RTs on "color lead" trials (996 ± 586) were significantly faster than RTs on "motion lead" trials (1235 ± 698), $t(16) = 3.77$, $p = 0.002$, *Cohen's D* = 0.90. The same pattern was found for the level of "hard": RTs on "color lead" trials (1269 ± 564) was also significantly faster than RTs on "motion lead" trials (1599 ± 782), $t(16) = 3.56$, $p = 0.003$, *Cohen's D* = 1.25.

For the condition in which relative timing equaled to 0 (i.e. color change and motion direction change occurred simultaneously), participants chose "color change first" at a response rate of 48% ± 7%. RT was shorter when participants chose "color change first" (1190 ± 683) than when participants chose "direction change first" (1408 ± 651), $F(1,16) = 22.56$, $p < 0.001$, ${\eta^2}_p = 0.59$, a pattern consistent with findings in other relative timing conditions.

As for response accuracy (Table 3), a two (lead condition: color lead versus motion lead) times three (task difficulty: easy, medium, and hard) ANOVA revealed only a significant main effect of difficulty, $F(2,32) = 34.71$, $p < 0.001$, ${\eta^2}_p = 0.68$. The main effect of lead condition was not significant, $F(1,16) = 2.24$, $p = 0.15$, ${\eta^2}_p = 0.12$, nor the interaction between the two factors, $F(2,32) = 3.36$, $p = 0.05$, ${\eta^2}_p = 0.17$.

The HDDM analysis revealed that the threshold (a) was lower for "color lead" than for "motion

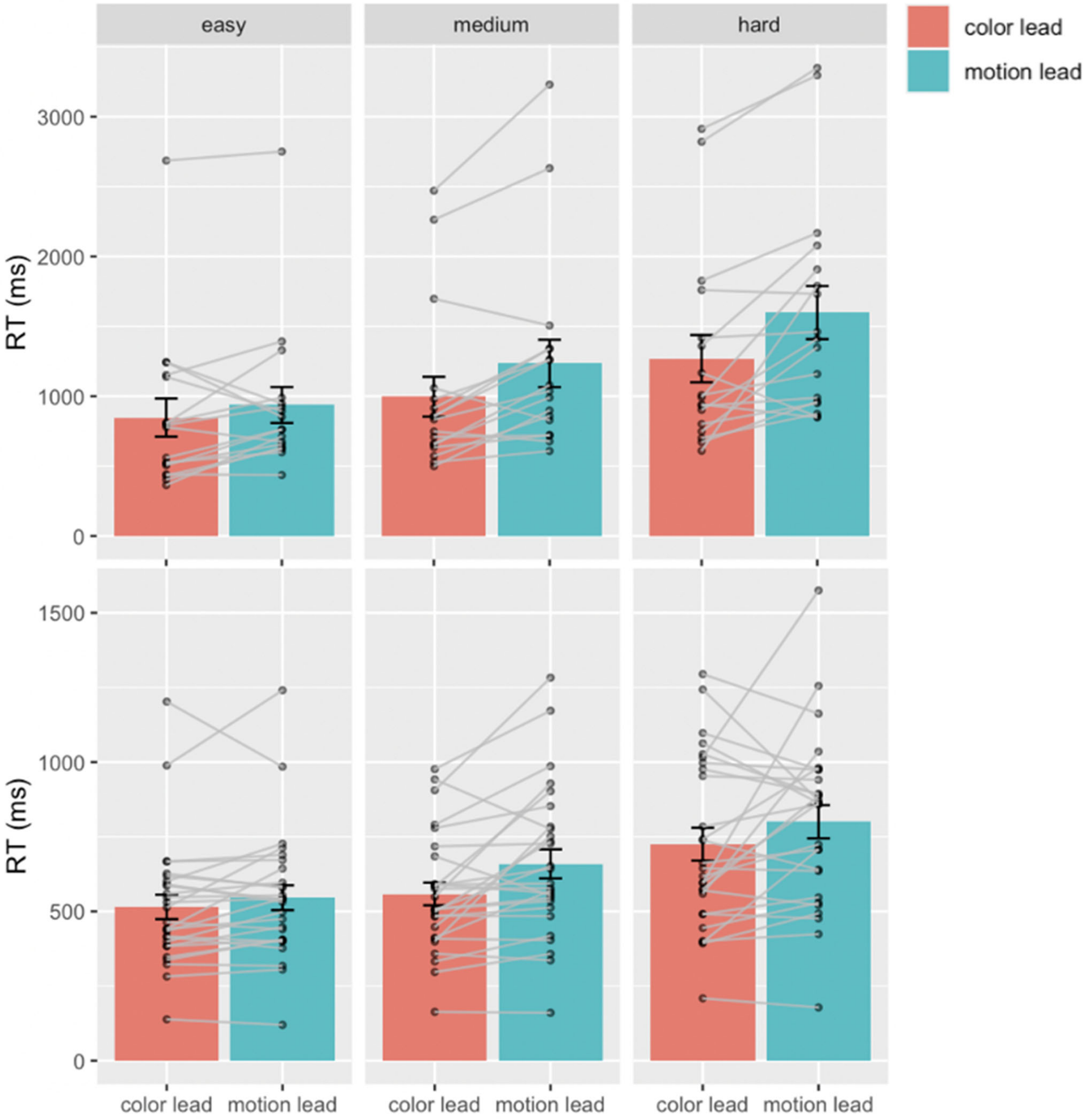

Figure 4. RT as a function of the relative timing condition and task difficulty in Experiment 2a (the upper panels) and Experiment 2b (the lower panels). Error bars denote SEM. Dots and lines denote individual data.

	Easy Color lead	Motion lead	Medium Color lead	Motion lead	Hard Color lead	Motion lead
Exp 2a ($N = 17$)	90 ± 10	94 ± 9	88 ± 13	85 ± 17	68 ± 16	78 ± 13
Exp 2b ($N = 27$)	96 ± 5	95 ± 6	92 ± 8	91 ± 12	74 ± 17	79 ± 18

Table 3. Mean accuracy in different conditions in Experiments 2a and 2b, with standard deviations shown after ±.

lead,” $P_{\text{posterier}}$ (color lead < motion lead) > 0.99, and non-decisional time (t_0) was longer for “color lead” than for “motion lead,” $P_{\text{posterier}}$ (color lead > motion lead) > 0.99. No difference was found between these two categories on drift rate (v), $P_{\text{posterier}}$ (motion lead < color lead) = 0.56. These results indicated that participants were less cautious in making a decision when the change in color occurred before (versus after) the change in motion direction, with more time cost of response execution (non-decisional time).

The pattern of results in Experiment 2b was parallel to that in Experiment 2a. Again, no significant difference was found between PSE (mean = −6 ms) and 0, $t(26) = -0.78$, $p = 0.44$, *Cohen's D* = -0.13. This null effect was confirmed by the $BF_{01} = 4.20$, suggesting that the null hypothesis was 4.20 times more likely to be true than the alternative hypothesis. For RTs of the correctly responded trials (see Figure 4, lower panel) after removing the correct trials (2.95% of all the trials), the ANOVA revealed a main effect of task difficulty, $F(2,52) = 43.42$, $p < 0.001$, $\eta^2_p = 0.63$, and a main effect of lead condition, $F(1,26) = 7.20$, $p = 0.01$, $\eta^2_p = 0.22$, although the interaction between the two factors was not significant, $F(2,52) = 2.03$, $p = .14$, $\eta^2_p = .07$. Thus, across all the three levels of task difficulty, participants responded faster to "color lead" trials (623 ± 247) than to "motion lead" trials (701 ± 272), $t(26) = -3.01$, $p = 0.006$, *Cohen's D* = 0.47.

For the condition in which the relative timing equaled 0, participants chose "color change first" at a response rate of 49% ± 7%. RT was shorter when participants chose "color change first" (671 ± 239) than when participants chose "direction change first" (749 ± 275), $F(1,26) = 11.46$, $p = 0.002$, $\eta^2_p = 0.31$, replicating the pattern in Experiment 2a.

For response accuracy (see Table 3), a two (lead condition: color lead versus motion lead) times three (task difficulty: easy, medium, and hard) ANOVA revealed only a significant main effect of difficulty, $F(2,52) = 60.64$, $p < 0.001$, $\eta^2_p = 0.70$, but no effect of lead condition, $F(1,26) = 0.28$, $p = 0.60$, $\eta^2_p = 0.01$, nor the interaction between these two factors, $F(2,52) = 1.17$, $p = 0.32$, $\eta^2_p = 0.04$.

The HDDM analysis revealed that the threshold (a) was lower for "color lead" trials than for "motion lead" trials, $P_{\text{posterier}}$ (color lead < motion lead) > 0.99, indicating again that participants were less cautious in making decisions over a change in color occurring before (versus after) a change in motion direction. Drift rate (v) was higher for "color lead" condition than for "motion lead" condition, although the effect was marginally significant from a frequency statistic prospective, $P_{\text{posterier}}$ (color lead < motion lead) = 0.07. No effects were found on non-decisional time (t_0), $P_{\text{posterier}}$ (color lead < motion lead) = 0.52 (different from Experiment 2a). Indeed, when we combined the data of Experiments 2a and 2b and conducted the HDDM analysis, we observed the same pattern of results as the pattern for Experiment 2b: the threshold (a) was lower for the "color lead" trials than for the "motion lead" trials, $P_{\text{posterier}}$ (color lead < motion lead) > 0.99; drift rate (v) was higher for the "color lead" trials than for the "motion lead" condition, $P_{\text{posterier}}$ (color lead < motion lead) = 0.08; but there was no effect on either non-decisional time (t_0), $P_{\text{posterier}}$ (color lead < motion lead) = 0.30.

General discussion

By overcoming some methodological deficits in previous studies, the current study re-examined CMA with both the color and motion correspondence tasks and the temporal order judgment task. Results consistently showed that participants perceive a change in color earlier and more efficiently than a change in motion direction regardless of whether the initial attention was led to color or motion direction (and whether the imperative dimension of stimuli the perceivers respond to was motion direction or color) in the correspondence tasks. Nevertheless, the imperative dimension of stimuli that the participants responded to did affect the size of the perceptual asynchrony, with CMA being larger in the motion correspondence task than in the color correspondence task. The analyses of RT and HDDM modeling in the TOJ task also demonstrated the relative efficiency of color change processing over motion direction change processing. Overall, the current study provides compelling evidence for the veracity of CMA.

With a relatively larger sample of participants and a within-subject design, we demonstrated in Experiment 1 that reversing the feature (motion versus color) participants attend to first in a trial (and hence subsequent the target dimension that participants respond to) does not reverse color-motion asynchrony. Past studies expressed concern over the role of attended feature on CMA in the correspondence tasks (e.g. Arnold, 2005; Clifford et al., 2003; Enns & Oriet, 2004; Holcombe & Cavanagh, 2008). CMA might result from the time cost of redirecting attention from color to motion direction (see Enns & Oriet, 2004). However, as suggested by Moutoussis (see Moutoussis, 2012 for a review), the small sample size used by these studies did not allow for any strong conclusions to be drawn. Nevertheless, with a large sample of participants, we did find that CMA was indeed diminished but not eliminated in the motion (versus color) correspondence task where participants attended to motion direction first and respond to color later.

Our results are consistent with the findings of Clifford and colleagues (2003), who found that the perception time advantage of color over orientation was decreased when participants attended to orientation (versus color) first. In their studies, participants completed an orientation correspondence task (what is the predominant orientation when the stimulus is red or green?) and the color correspondence task (what is the predominant color when the stimulus is inclined to the left or right?) in different runs of the experiment. They found a weaker classical CMA in the color correspondence task relative to the orientation correspondence task. These results together suggest that attention can modulate the magnitude of perceptual asynchrony, perhaps by speeding up the processing of the attended attribute ("prior entry" effect, attending to a particular stimulus mean that it will be perceived earlier in time than if attention had been directed elsewhere, see Spence & Parise, 2010; Sternberg & Knoll, 1973). It is also possible that switching attention from one dimension to another dimension of the stimulus leads to longer perceptual latency of the latter dimension than the former one. Thus, CMA is weaker when participants switch attention from motion direction to color in the color (versus motion) correspondence task.

Although the TOJ task could serve as a more straightforward task to scrutinize CMA, past studies using this task produced mixed findings (see Table 2). Here, in Experiment 2, we used both RT as well as PSE as an index of the perceptual efficiency of motion direction and color. Results of PSE showed no sign of CMA, in line with several previous TOJ studies implicating that participants can precisely perceive the relative timing of the change in color and the change in motion direction (Bedell et al., 2003; Clifford et al., 2003; Linares & Lopez-Moliner, 2006; Nishida & Johnston, 2002). However, the RT and HDDM analyses showed that participants respond faster and less carefully when the change in color occurs before (versus after) the change in motion direction, whether the response is timed or not. Consistent with our hypothesis, with the same objective relative timing, the relative timing between a change in color and a change in motion direction can be subjectively stretched when the change in color occurs before the change in motion direction but compressed when the change in color occurs after the change in motion direction.

It seems that it is viable to use RT as an index of processing efficiency in TOJ tasks, at least in certain circumstances. The TOJ paradigm has been widely used as an accurate measure of processing latency (e.g. Jaśkowski, 1992; Roufs, 1974), temporal resolution (e.g. Babkoff, Zukerman, Fostick, & Ben-Artzi., 2010; Szelag, Jablonska, Piotrowska, Szymaszek, & Bednarek, 2018), sequencing ability (e.g. Szymaszek, Dacewicz, Urban, & Szelag, 2018; Fostick & Babkoff, 2013), and many other processing capacities in the millisecond time range in previous studies. For processing latency, it has been shown that PSE in the TOJ task is less sensitive than RT in the detection task given the same intensity change of the stimulus property (see Jaśkowski, 1992; Miller & Schwarz, 2006). If the perceptual latency of stimulus 1 is shorter than that of stimulus 2, then the RT should be shorter when stimulus 1 occurs before stimulus 2 than when stimulus 1 occurs after stimulus 2 in a TOJ task. With a relatively large sample size, across the three levels of task difficulty, we observed exactly this pattern. Moreover, with the help of HDDM, the perceptual decision making process was characterized by important parameters such as drift rate and threshold in Experiment 2. The decision threshold was lower for the "color lead" trials than the "motion lead" trials, indicating a bias toward speed in the accuracy-speed trade-off process. Participants were more cautious to make decisions in the "motion lead" condition than in the "color lead" condition. Additionally, the speed of evidence accumulation (i.e. drift rate), was higher in the "color lead" condition than in the "motion lead" condition, although the difference was only marginally significant for the combined data, $P_{\text{posterier}}$ (color lead $<$ motion lead) $= 0.08$. This result might suggest a more efficient process to detect a change of color than a change of motion direction, a proposition consistent with the traditional CMA hypothesis (Amano et al., 2007). Taken together, the analyses of RTs and HDDM help shed light on the processing efficiency in the TOJ task.

Although RTs could be informative, many previous psychophysical studies using the TOJ task simply ignored this measure (e.g. Bedell et al., 2003; Christie, Osborn, McMullen, Pawar, Thomas, Bensmaia, Celnik, Fifer, & Tenore, 2022; Clifford et al., 2003; Linares & Lopez-Moliner, 2006; Lungu, Rothen, & Terhune, 2021; Nishida & Johnston, 2002; Szelag et al., 2018; Szymaszek et al., 2018), presumably because of sample size or because of concerns over the locus of the effect (e.g. perceptual processing, response selection, or response execution). The present study demonstrates that, with appropriate manipulation and modeling, the cognitive processes underlying a particular experimental effect could be revealed from the RT data.

In conclusion, by using different tasks and by overcoming design deficits in previous studies, the current study obtained solid and consistent data demonstrating the veracity of color-motion asynchrony. Our results support the proposal that the color and motion properties of stimuli are processed not only in functionally different brain areas but also with different temporal characteristics. Moreover, by analyzing the response time data in the TOJ task, the current study points to a general viability of analyzing response times in traditional psychophysical measures.

Keywords: color-motion asynchrony (CMA), temporal order judgment task (TOJ), correspondence task, drift-diffusion modeling (DDM)

Acknowledgments

The authors thank Yanyu Zhang for her constructive comments on a draft version of the manuscript.

Supported by the National Natural Science Foundation of China (31861133012).

Author contributions: All authors developed the study concept and contributed to the study design. Data collection and analysis were performed by J.H. and Z.S. Manuscript preparation was conducted by J.H. and X.Z. All authors approved the manuscript for submission.

Commercial relationships: none.
Corresponding author: Xiaolin Zhou.
Email: xz104@pku.edu.cn.
Address: School of Psychological and Cognitive Sciences, Peking University, Beijing 100871, China.

*JH and ZS contributed equally to this work and should be considered as co-first authors.

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