Processing fluency for visual synchrony perception

Joshua S. Bamford[1,2], Bronwyn Tarr[2,3], Emma Cohen[2,4]

[1]Centre of Excellence in Music, Mind, Body and Brain, University of Jyväskylä

[2]Institute of Human Sciences, University of Oxford

[3]The London Interdisciplinary School

[4]Wadham College, University of Oxford

Contributions

JSB: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualisation, Project Administration. BT: Conceptualisation, Writing – Review & Editing, Supervision. EC: Conceptualisation, Resources, Writing – Review & Editing, Supervision, Funding Acquisition.

Conflict of Interest

The authors have no conflicts of interest to declare.

Acknowledgements

This project received funding from the John Fell Fund (7908) and the Academy of Finland (332331 and 346210). The authors wish to acknowledge Eric Clarke and Bahar Tuncgenc for their helpful comments on a draft of this manuscript.

Processing fluency for visual synchrony perception

Abstract

Prior research has found that interpersonal synchrony increases social closeness and cooperation: this is often referred to as the synchrony-bonding effect. Most explanations for this synchrony-bonding effect rely upon higher-order social cognition (e.g. shared goals or self-other merging). Relatively little attention has been given to the perceptual experience of synchrony, and the low-level perceptual mechanisms involved, such as processing fluency. In two pre-registered experiments, we tested the novel hypothesis that synchrony (congruent movement) is easier to process than non-synchrony. In Study 1, no effect of direction congruency on performance was detected. However, Study 2 found a significant effect of speed congruency. This indicates decreased processing load when stimuli are moving at the same speed. We then discuss how these reduced visual stimuli may relate to naturalistic periodic movement. Crucially, the effect observed here does not rely upon social stimuli and may operate at an early stage of perceptual processing. This is an initial step in establishing a novel theory of the synchrony-bonding effect, based upon the principles of processing fluency.

Keywords: synchrony, entrainment, visual perception, flanker, motion, processing fluency, cognitive load.

1 Introduction

Social behaviour regularly features moments of synchrony that display or reinforce social affiliation. Behavioural synchrony is characterised by a strict temporal locking of actions, though the exact shape and kind of the actions may or may not be matched (Bernieri & Rosenthal, 1991). This is exemplified in activities such as music, dance, rowing and marching (McNeill, 1997). Synchrony may emerge spontaneously, as rhythmic sounds often induce involuntary bodily entrainment in adults (Zelechowska et al., 2020). This capacity for spontaneous sensorimotor synchronisation appears to be limited to a small and distantly related number of animal species, among which humans display a particular ability (Fitch, 2013). Despite synchrony's ubiquity, experimental research has only recently begun to uncover social effects and underlying causal pathways.

Recent studies of the effects of behavioural synchrony on social affiliation and bonding demonstrate that people feel a sense of social closeness and are more likely to exhibit pro-social behaviour towards someone with whom they have previously synchronised – termed the *synchrony-bonding effect* (Hove & Risen, 2009; Mogan et al., 2017; Rennung & Göritz, 2016; Savage et al., 2021; Vicaria & Dickens, 2016). Perceiving others synchronising can also elicit a response: synchronised groups are perceived as more formidable and bonded (Lee et al., 2020), and watching synchronised performances leads to a perception of beauty, aesthetic appreciation, and greater enjoyment than non-synchrony (McEllin et al., 2020; Vicary et al., 2017).

Participation in, and perception of, synchrony have these social effects, and various causal pathways have been proposed in recent research. Some theories rely upon higher-order cognitive processes, such as shared goals, shared intentions, or a perception of self-other similarity (Demos et al., 2012; Reddish et al., 2013; Valdesolo & DeSteno, 2011). Other accounts have suggested that synchrony biases attention to select synchronous stimuli

(Bamford et al., 2016; Cirelli et al., 2014; Woolhouse et al., 2016). However, it is not clear why our attention should be drawn to synchrony, nor how synchrony is involved at other stages of stimulus perception. Here, we propose that the social effects of behavioural synchrony arise in part through low-level perceptual mechanisms, specifically via a domain-general processing fluency effect. The present study develops and tests this proposal and begins to fill this gap in our understanding of the causal role of general perceptual principles in the synchrony-bonding effect.

1.1 Processing Fluency

Processing fluency is a general explanatory principle that can be applied to a range of preference judgements. It is not domain-specific and suggests that the ease with which a stimulus is processed provides an intrinsic reward (Winkielman et al., 2003). By rewarding action that seeks out easy experiences, processing fluency effects provide motivation that can function to optimise energy costs of cognition (Leder, 2013). Stimuli that are easy to process evoke positive feelings, which in turn provide information about the stimuli (Schwarz, 2012). Another suggestion is that fluency is a cue for familiarity, without having to rely upon memory processes (Winkielman et al., 2003); one of the most reliable means of generating processing fluency is to have had prior exposure to a stimulus, and so a fluently processed stimulus is more likely to have been encountered previously than stimulus that is more difficult to process. In this case, if fluency is experienced because of the intrinsic qualities of the stimulus, rather than because of the observer’s prior experience, this fluency heuristic may lead to an illusion of familiarity (Reber et al., 2004). Processing fluency effects could also be understood as prediction fulfilment in a predictive processing framework. In predictive processing, the brain is testing predictions about the world against sensory stimuli (Rao & Ballard 1999). Any prediction error – or free-energy – would require updating the internal predictive model, which is effortful, whereas having a prediction fulfilled would be rewarding (Friston & Kiebel, 2009;

Clark 2015). The effect is the same: an individual can experience a positive reward from a stimulus that is predictable and easy to process – either by the structural simplicity of the stimulus, or through prior exposure.

Processing fluency is a general principle that has been successfully applied to a wide range of stimuli. It has been used to explain preferences for art, visual patterns, music, and font styles (Reber et al., 2004). Processing fluency has also been applied to some social judgements, as an explanation for why people are more likely to be prejudiced against others who are harder to understand (Lick & Johnson, 2015). Despite its generality, processing fluency has yet to be tested for synchronised stimuli. In a purely theoretical exploration, Wheatley and Sievers (2016) suggested that interpersonal synchrony may be more efficient to process by consolidating streams of information about the self and other, leading to a state of fluency. Hove and Risen (2009) also raised the possibility that synchrony may be easier to process than non-synchrony. The suggestion was offered in a brief footnote and has not since been theoretically developed or tested.

Many observations associated with the synchrony-bonding effect and the perception of synchrony bear similarity to the effects of processing fluency. Moving in synchrony with another increases their likability (Hove & Risen, 2009). Meanwhile, greater synchrony in performance increases viewer enjoyment and aesthetic ratings (McEllin et al., 2020; Vicary et al., 2017). Similar effects on liking and aesthetic perception are observed in typical processing fluency studies (Reber et al., 2004). The structure of synchronised stimuli also fit within the existing criteria for fluent processing. Synchrony is usually sustained over an extended period of time (Bispham, 2018), and repeated exposure to a stimulus builds familiarity and fluency for that stimulus (Reber et al., 1998; Winkielman & Cacioppo, 2001). Fluently processed stimuli often have simple features and contain a degree of redundancy, such as in symmetrical patterns (Makin et al., 2012). This is analogous to the repetitive movement patterns usually observed in synchronised action, which often exhibit a simple rhythmic structure (Polak et al., 2018). Synchronised stimuli share traits with other stimuli that are easy to process, and the resultant processing fluency potentially produces positive affective and social consequences for the perceiver(s).

Synchronous action entails the grouping of visual, auditory, or other sensory objects (Hukin & Darwin, 1995; Rideaux et al., 2016). For example, when two people tap or drum together in synchrony, the listener may perceive the two objects and combine them together to form a larger whole. Wheatley and Sievers (2016) described a phenomenon of interpersonal streaming which may occur during synchrony. As such, Gestalt grouping principles can inform the perceptual processes involved.

Gestalt grouping, first described by Wertheimer (1938), outlines a set of principles through which objects are grouped together. Cues such as proximity and similarity result in many objects being seen as part of a larger whole. The principles apply to both visual and auditory perception, although the process of grouping sounds into “streams” is usually referred to as Auditory Scene Analysis (Bregman & Campbell, 1971). Crucially, synchrony of sound or movement, or of the onset of an event, is a strong cue for grouping in both auditory and visual domains (Hukin & Darwin, 1995; Rideaux et al., 2016). When multiple stimuli act in synchrony with each other, they could be perceived as one object due to gestalt grouping principles or auditory streaming depending on the modality (Hukin & Darwin, 1995; Pressnitzer et al., 2011; Rideaux et al., 2016; Wertheimer, 1938). However, ambiguity in grouping cues requires increased attentional effort to resolve (Dolležal et al., 2014). In the acoustic domain, additional perceptual objects provide a distraction, demanding more attentional control (Hughes et al., 2013; Zeamer & Fox Tree, 2013). These grouping principles could explain why synchrony is easier to process than non-synchrony.

1.2 The Present Study

Processing fluency may be a causal factor underlying the synchrony bonding effect. However, there are no studies that specifically test this. Before testing the social effects of processing fluency arising from synchrony, it must be established whether processing fluency arises from synchrony at all. Thus, this study tests whether synchrony is easier to process than non-synchrony in the visual domain.

Ease of processing is regularly measured using reaction times (Reber et al., 2004). However, previous research has found that participants may choose to sacrifice speed for accuracy (Dutilh et al., 2011). This speed-accuracy trade-off may be accounted for by instructing participants to focus on either speed or accuracy, or by combining speed and accuracy into an overall performance score. The present study used the latter approach, combining reaction time and error rate into a performance score to infer the processing load of the tasks, while also instructing participants not to sacrifice accuracy in their responses.

Reaction times have rarely been studied in the context of synchronised action because synchrony requires precise timing by its nature. Reaction times can be influenced by spontaneous entrainment to a periodic stimulus, as people will tend to respond in time with the stimulus (Killingly et al., 2021). Therefore, the present study uses non-periodic stimuli, involving continuous movement without any rhythmic structure.

Most synchrony-bonding studies have used periodic stimuli. In periodic movement, velocity changes in a regular, oscillating pattern. When two oscillators are in synchrony, their velocities will always be changing, but will have a consistent relationship between them. By using non-periodic stimuli with a consistent velocity, the present study avoids spontaneous entrainment to the stimuli. As a consequence, it focuses on the perception of brief snapshots of coordinated movement between multiple stimuli.

The stimuli used in the present study were based upon the animated Flanker paradigm developed by Lange-Malecki and Treue (2012), but with Gabor patches similar to those used by De Valois and De Valois (1991). Gabor patches are generated through the convolution of sinusoidal and Gaussian functions (Figure 1). They can be animated so that the bars appear to drift and are often used to study motion perception (e.g. Amano et al., 2009; De Valois & De Valois, 1991; Rideaux et al., 2016). Previous studies have found that animated Gabor patches moving in synchrony are perceptually grouped together (Rideaux et al., 2016). Animated Gabor patches are thus ideal stimuli for studying processing fluency that may arise through perceptual grouping.

Figure 1. A single Gabor patch.

Developed by Eriksen and Eriksen (1974), the Flanker task is a method of studying attention control. Typical flanker tasks involve a central ‘target’ stimulus, surrounded by ‘flanker’ stimuli in a horizontal line either side. The stimuli are usually static images, such as a letter or an arrow, that correspond to a keyboard response. In congruent conditions, the ‘target’ and ‘flankers’ are identical, while in incongruent conditions they are not. Participants complete many trials, with the average reaction time and accuracy of responses to the stimuli taken as measures of the effect of visual distraction between congruent and incongruent conditions (Eriksen & Eriksen, 1974). Prior research has demonstrated that reaction times can be reliably measured with Flanker tasks on an online platform (Crump et al., 2013; de Leeuw, 2015; Pinet et al., 2017).

Although a well-established test for the perception of static images, there are few examples of animated Flanker tasks. One study, with a relatively small sample of 21 students, directly compared the effects of moving and static flankers (Lange-Malecki & Treue, 2012). In all conditions, participants had to report the direction indicated by the target, but in the static condition the stimuli were all triangles pointing either left or right, while in the moving condition the stimuli were random dots moving within a defined circle. The authors found similar effects of congruency in both of these conditions (Lange-Malecki & Treue, 2012). However, the aim of their study was not to study synchrony *per se*, and their findings were based on a very small sample. Lange-Malecki and Treue (2012) did demonstrate that the flanker effect exists for moving as well as static stimuli, which the present study investigates further with the specific aim of testing the processing load of synchrony.

Across two preregistered experiments, we tested the hypothesis that synchronised stimuli are easier to process, as measured by performance on a Flanker task, than non-synchronised stimuli. Study 1 used only one manipulation, having stimuli that were either congruent or incongruent in direction. Study 2 involved the addition of a speed manipulation. We predicted highest performance when the target was moving at the same rate and direction as the flanker stimuli. Both experiments were conducted online using the novel Gabor-Flanker task. This is a variation on the animated Flanker task developed by Lange-Malecki & Treue (2012), although featuring animated Gabor patches such as those used by De Valois and De Valois (1991). If performance is better in the congruent trials, this would indicate that the target and flanker stimuli may be perceptually grouped together, reducing processing load. Lower processing load when perceiving synchronised stimuli than when perceiving non-synchronised stimuli would suggest that some of the positive effects of synchrony could, at least in part, be explained by processing fluency.

2 Study 1

In a within-subjects design, Study 1 tested the effect of synchrony on processing load, as measured by reaction times and a composite performance score. We utilised novel stimuli by constructing a Flanker task using Gabor patches, in which the movement of the target patch was either congruent or incongruent with the movement of the flankers by moving either in the same or opposite direction (Lange-Malecki & Treue, 2012). In line with our hypothesis that synchrony is easier to process than non-synchrony, we predicted that participants would make faster and more accurate responses when the flanker stimuli were moving congruously (i.e., in the same direction) with the target/central stimulus, compared with when they moved incongruously (i.e., in different directions). This experiment was preregistered.[1]

2.1 Participants

This study was conducted online, with participants recruited using snowball sampling methods through social media (Facebook, Twitter, Reddit). A sample of 73 participants (45 female, 27 male, 1 other) completed the study, exceeding the target sample size of 71 (based upon a power analysis with d = .3, α =. 05, 1-β = .8). Most participants were living in Western countries, with the majority coming from the United Kingdom (34.2%), the rest of Europe (30.1%), Australia (23.3%), and North America (8.2%), and had a mean age of 31.01 (*SD* = 10.3, range = 20:62). Participants were required to have normal or corrected vision, and to have access to a device with a keyboard. All participants reported fulfilling these criteria, and gave informed consent to participate in this study, in accordance with the ethics requirements of the university's ethics board.

Any incomplete responses were excluded. Mean time to complete the perceptual component of the study (excluding the demographic questionnaire) was 452.82 seconds (*SD* =

---

[1] http://aspredicted.org/blind.php?x=cj7bd7

112.62). One participant was excluded from this calculation for having an extraordinarily long completion time (12296.4 seconds), although most of this time was taken on the first screen, and there was no unusual behaviour otherwise on the task. It is suspected that this participant left the page open before beginning the task itself, and thus their data were retained for analysis.

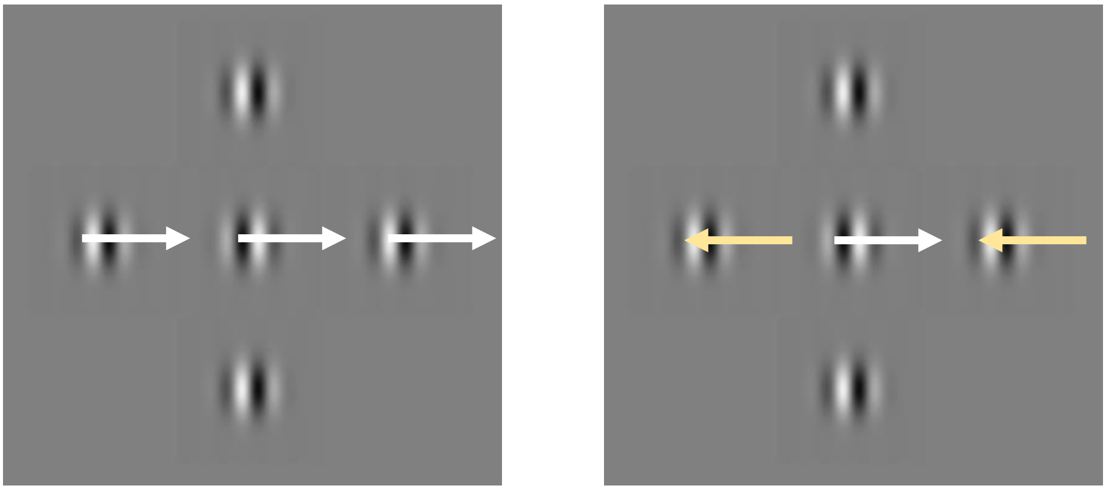
2.2 Materials

The online study consisted of two parts: a short demographic questionnaire and the Gabor-Flanker task. The animated Gabor stimuli in this study were generated in MATLAB using a function available in Online Materials[2]. Three Gabor patches were generated in this way: static, left-movement, right-movement. Each individual Gabor patch was 150 pixels in diameter, with a period length of 1cm, and the animated patches moved at a rate of 1cm/s. During development of the task, pilot participants had reported feeling disoriented when all the stimuli were moving, so static patches were added above and below the target to act as a visual reference point. The Gabor-Flanker task presented five Gabor patches (one target, two flankers, two static references) arranged in a diamond (Figure 2). There were two conditions in a within-subjects design: a congruent (synchrony) or incongruent (non-synchrony) condition. In the congruent condition, the target Gabor patch moved in the same direction as those either side of it, and in the incongruent condition it moved in the opposite direction to the flankers. The Gabor patches immediately above and below the target were always static. The task itself was built using jsPsych (de Leeuw, 2015), and the script is available on Online Materials[3]. Because the task was completed by participants online, on their own computers, specific details of resolution and screen size could not be controlled.

---

[2] https://github.com/bamford-js/GaborGen

[3] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Experiment



a) Congruent b) Incongruent

Figure 2. Arrangement of stimuli in the Gabor-Flanker task. The central Gabor patch was always the target stimulus, and the patches immediately above and below it were always static, while those to its left and right were animated. The left and right flanker stimuli either moved in the same direction as the target (congruent) or in the opposite direction (incongruent). Arrows are for illustration purposes only.

2.3 Procedure

Participants completed the demographic questionnaire in Qualtrics, before being presented with the Gabor-Flanker task. The on-screen instructions explained that this study aimed to investigate motion perception. No details of the hypotheses were divulged. Participants were instructed to categorise the direction of the target (either left or right) and to respond to each trial as quickly as possible, without sacrificing accuracy. Previous studies have found that participants adopt two different modes of thinking in reaction time experiments: stimulus-controlled behaviour, and guessing (Dutilh et al., 2011). By emphasising the need for accuracy, guessing can be reduced.

The Gabor-Flanker task was initially presented in 8 practice trials, followed by three blocks of 60 trials. Participants were invited to take a short break between blocks, to prevent fatigue. Each block contained 30 trials from each condition (congruent and incongruent), presented in randomised order. Participants had a maximum of 2000 ms in which to respond to each trial, or that trial would be marked as incorrect. Responses were given by pressing either the ‘F’ or ‘J’ key on their keyboard, for ‘left’ and ‘right’ respectively, to indicate the direction of the motion in the target Gabor patch. Following every trial, there was a short pause of between 500 and 2000 ms in duration. The random pause duration was to prevent the task from having any intrinsic rhythm. The script may be found in Online Materials[4].

2.4 Analysis

Raw data were exported from Qualtrics. Reaction time (RT) – the time from initial presentation of a stimulus until the participant’s button press – was recorded for each trial within the online JavaScript application. For each block of 30 trials, a mean reaction time for correct responses was calculated, as well as an accuracy rate (percentage of correct responses in a block). Accuracy (%) was divided by mean RT (ms) on correct trials to give a composite performance score (hereafter “performance”). This was calculated for each participant, in each block, for every condition, and then scaled by 100 for readability. This is an adaptation from Lange-Malecki and Treue (2012), who used an inverse efficiency measure to account for different accuracy rates between conditions. Although participants were instructed not to sacrifice accuracy, it is possible some may have done so to optimise RT. Therefore, RTs alone may not capture the true difficulty of the task. As a combined measure, performance accounts for any potential speed-accuracy trade-off. A Pearson’s correlation was used to confirm a negative relationship between accuracy and RT.

To test the hypothesis that the non-synchronised (incongruent) trials are more difficult to process than synchronised (congruent) trials, a repeated measures ANOVA was used to test the effect of flanker condition (stimulus) and presentation order (block) on performance. Presentation order was included to investigate any practice effects.

---

[4] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Experiment

Data were processed in Python, statistical tests were conducted using Pingouin (Vallat, 2018), and figures were produced with Seaborn (Waskom, 2021). The data and script for analysis may be found in Supplementary Online Materials[5].

2.5 Results

Descriptive statistics for all measures on the stimulus conditions are reported in Table 1. Five participants who scored more than 2.5 standard deviations from the mean on performance were removed as statistical outliers. The level of 2.5 standard deviations has been used in previous processing fluency studies as the basis for exclusion (Reber & Schwarz, 1999).

A medium, positive, significant correlation was observed between mean reaction time and accuracy, $r = 0.277$, $p < .001$, indicating a trade-off between reaction time and accuracy (see Figure 3), and justifying the use of a composite performance score.

Table 1. *Descriptive statistics for reaction time, accuracy, and composite performance across the two stimuli conditions, with outliers excluded.*

	Reaction Time (ms)		Accuracy (%)		Performance (%/ms)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Congruent	573.6	100.2	97.76	4.142	17.46	2.605
Incongruent	578.0	105.2	97.70	3.699	17.32	2.460

---

[5] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Analysis

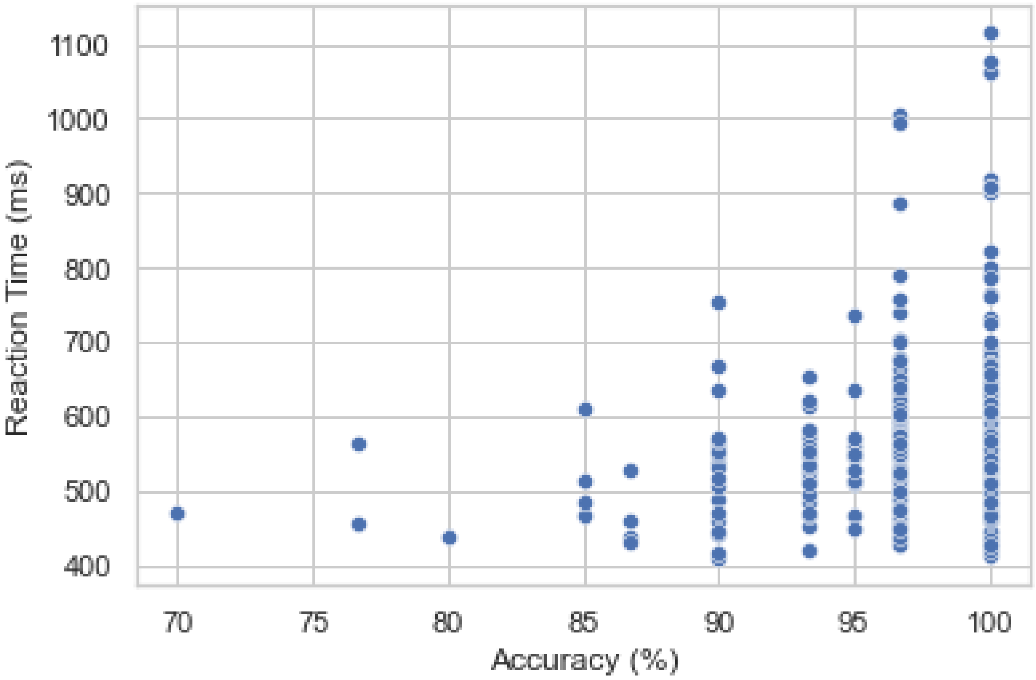


Figure 3. Mean reaction time (ms) on correct trials per block, plotted against accuracy (% correct) per block. Blue dots correspond to the mean RT and accuracy for each participant.

Using the composite performance measure (accuracy/reaction time), the assumptions of equal variances were met for both the stimulus condition, *W* = 1.04, *p* = .309, and block condition, *W* = 2.270, *p* = .105. However, the assumption of sphericity was violated for the block condition, $X^2(2)$= 23.76, *p* < .001, so a Greenhouse-Geisser correction was applied. The repeated measures ANOVA found a significant effect of block on performance, but no effect of stimulus condition (see Table 2 and Figure 4). Post-hoc, Bonferroni corrected t-tests revealed significant differences between Block 1 and Block 2, *t*(66) = -4.842, *p* < .001, and between Block 1 and Block 3, *t*(66) = -4.138, *p* < .001, suggesting a significant practice effect. There was no significant effect of stimulus condition on performance.

Table 2. *Repeated-measures ANOVA for the effect of stimulus condition and block number on performance.*

Effect	*df*	*F*	*p*	η_p^2	ε
Stimulus	1, 66	1.469	.230	0.022	1
Block	2, 132	16.30	<.001	0.198	0.766
Stimulus * Block	2, 132	0.529	.578	0.008	0.930

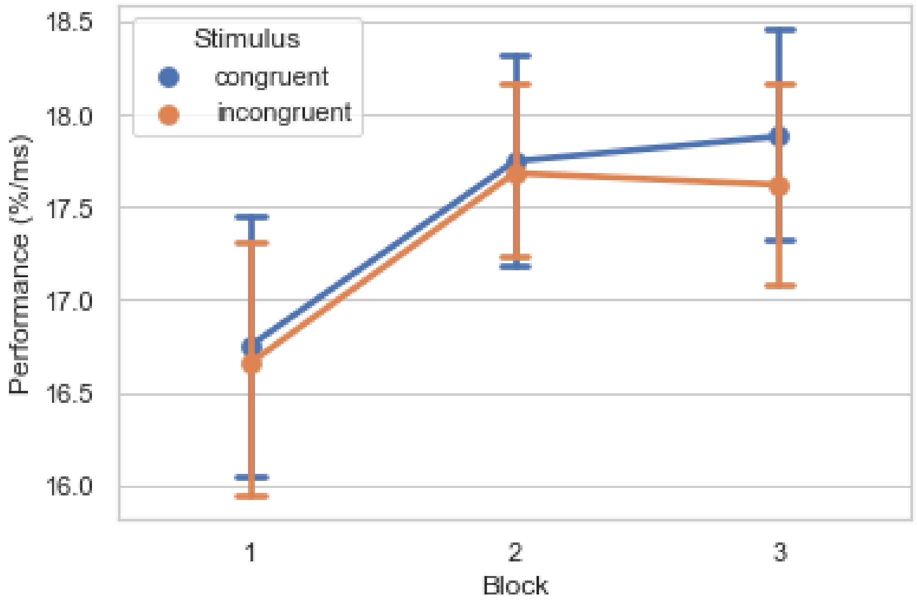


Figure 4. Plot of each participant’s composite performance score (accuracy/reaction time) in both the congruent and incongruent conditions, against presentation order (block number). All data are presented, including subjects that scored below chance level accuracy. Error bars show 95% confidence intervals.

2.6 Discussion

Study 1 tested the effect of synchrony on perceptual fluency, operationalised as a performance measure combining both accuracy per block and reaction time (RT) for correct trials. In this case, synchrony within a trial was manipulated through congruency of direction between the target and flanker stimuli. Trials were divided into three blocks, for the purpose of calculating accuracy rates and to investigate order effects. Significant order effects were observed, with participants showing increased performance on later blocks. This indicates a practice effect, which is consistent with previous literature on attention control tasks such as the Flanker (Chen et al., 2013). However, the observed effects of the stimuli were more mixed.

No effect was found of stimulus condition on performance. It should be noted, however, that there were five outliers excluded for being greater than 2.5 standard deviations from the mean. These participants also scored below 50% accuracy (chance level) on at least one condition within at least one of the blocks. In every case this was only for the incongruent condition.

Given that the study was conducted online, and the participants' behaviour during the task could not be observed, it is possible that they had either misunderstood the task or were distracted. However, the presentation of stimulus type was randomised for each trial, and the increased rate of errors in the incongruent condition seems systematic for some participants. This could be because they found these trials more difficult to perceive, failing to correctly identify the direction of motion. All participants should have had normal or corrected vision, but it is possible that some participants had a vision or attention impairment that they either did not disclose or of which they were not aware. Alternatively, some participants potentially experienced something akin to the wagon wheel illusion, in which a stimulus appears to move backwards because of a mismatch between the rate of movement and the frame rate of the video (Purves et al., 1996), although the frame rate of modern computer monitors (usually at least 50Hz) should preclude this. Lange-Malecki and Treue (2012) also observed a reduced accuracy rate for incongruent moving flankers, although they did not report whether this disproportionately affected some participants more than others.

Typically, a congruency effect is observed in Flanker tasks, with reaction times being faster when the target stimulus is congruent with the flankers (Chen et al., 2013; Eriksen & Eriksen, 1974), and this has previously been observed in animated Flanker tasks similar to those in the present study (Lange-Malecki & Treue, 2012). Study 1 failed to replicate the results of Lange-Malecki and Treue (2012), though differences in design must be acknowledged. In both studies, the incongruent conditions were incongruent only in direction. However, Lange-Malecki and Treue (2012) used stimuli with moving dots, rather than the animated Gabor patches presented here. The dots used by Lange-Malecki and Treue (2012) were more visually complex, appearing as more objects on the screen, and thus less susceptible to being grouped together. Conversely, two Gabor patches are likely to be perceived as one object (Rideaux et al., 2016), even with opposing directions of motion. Because of this general difference in visual complexity, incongruency in Gabor patch direction may not have been difficult enough to register a difference in reaction time, when compared to incongruency in dot movement.

The null finding here, with stimuli that exhibit a consistent velocity, may also be understood in terms of periodic motion. In natural perception of synchrony, objects may be moving in different directions and/or at different speeds at any given moment. Natural oscillators exhibit periodic movement in which direction changes at regular intervals, while the stimuli presented here maintain a consistent direction. Despite the Gabor patches themselves being sinusoidal, their velocity remains consistent, and the temporal relationship between the target and its flankers is constant within a trial.

In synchrony studies, antiphase coordination is usually still considered to be synchronised (Repp, 2005). This occurs when two agents have a stable temporal relationship, except that one agent reaches the peak of its motion as the other is at its trough. The derivative (velocity) of these two waves would always be moving in opposite directions, at the same speed: just as the incongruent condition presented here. Therefore, incongruency in this experiment could be considered to be a derivative of antiphase synchrony, and thus not a true representation of the perceptual experience during a moment of non-synchrony.

When two oscillators move in synchrony, they will always be matched in velocity at any timepoint. Study 1 had one incongruent condition, in which direction was opposing but speed remained matched. In non-synchronised movement between two oscillators, speed usually also differs at any given time between them. To investigate the effect of both speed and direction, Study 2 includes a speed manipulation as an additional form of incongruency within the Flanker paradigm.

3 Study 2

Study 2 aimed to replicate and extend the results of Study 1 by examining the effect of a speed manipulation. In Study 1, the target was either moving in the same, or opposite, direction to the flankers. Study 2 also varied the rate of movement between the target and flankers in a 2x2 within-subjects design, with each participant completing four conditions: speed congruent – direction congruent (SC-DC), speed incongruent – direction congruent (SI-DC), speed congruent – direction incongruent (SC-DI), and speed incongruent – direction incongruent (SI-DI).

We hypothesised that speed-incongruency would have a negative effect on performance. Based upon the results of Study 1, no effect of direction-incongruency was expected. There were no specific hypotheses about interactions between the two factors. On one hand, there could be an additive effect of increased processing difficulty when both factors are incongruent. On the other hand, the target may become so different from the flankers, based on Gestalt grouping principles, that it becomes easier to perceive separately. This experiment was preregistered.[6]

---

[6] https://aspredicted.org/blind.php?x=wm8g3c

3.1 Participants

Participants were recruited online through the same methods as Study 1, however with an entirely new sample (no participants from Study 1 took part in Study 2). The minimum sample size was 62, for a repeated-measures ANOVA of small-medium effect size ($\alpha = .05$, $1-\beta = .8$). A total of 82 participants completed the task (49 female, 30 male, 3 other; mean age of 31.83). The majority of participants were from the UK (45.8%), the rest of Europe (32.3%), Australia (10.8%), North America (8.4%), and Asia (2.4%). Study 2 had the same selection criteria as Study 1. All participants reported having normal or corrected vision and gave informed consent according to the university's ethics requirements. This study was approved by the Departmental Research Ethics Committee as an extension of Study 1.

Mean completion time for the perceptual component of the study (excluding the demographic questionnaire) was 638.70s (*SD* = 174.37). Two participants were excluded from this calculation for having unusually long times (2279.14s and 2764.98s) although the excessive time was spent on the first screen, and otherwise they completed the task as expected, so their data were retained for analysis. Mean completion time including these participants was 684.63s (*SD* = 341.40). Incomplete responses were excluded.

3.2 Materials

Study 2 consisted of the same demographic questionnaire, and a similar Gabor-Flanker task to that used in Study 1. Four Gabor patches were generated using the same MATLAB script as Study 1, with both left and right animated patches at both slow and fast speeds for each condition. The fast Gabor patches moved at 1cm/s, the same rate as those in Study 1, while the slow patches moved at 0.5cm/s. The precise parameters to generate these Gabor patches are provided in Supplementary Online Materials[7]. Each patch was 150 pixels in

---

[7] https://github.com/Social-Body-Lab/fluency-through-synchrony/blob/main/Study1/GaborGen.m

diameter. These were then arranged into the same diamond-shaped configuration as Study 1 (see Figure 2), although with the added speed manipulation. As with Study 1, the Gabor patches on the vertical axis were held static to use as a visual anchor. Four conditions (as listed above) were constructed based on the relationship between the target Gabor patch in the centre and the two flankers to the left and right. All possible variations of speed and direction existed within these conditions.

3.3 Procedure

Participants took part in the study remotely. They were instructed to use a home computer with access to a keyboard, in a quiet environment, free from distractions. Participants completed the short demographic questionnaire in Qualtrics. This was followed by the perception task, which was embedded as a JavaScript App within Qualtrics. The script may be found in Supplementary Online Materials[8]. Participants were given similar instructions to Study 1.

There was a practice block of 16 trials, followed by five blocks of 48 experimental trials. This resulted in 60 experimental trials in each of the four conditions, presented in a randomised order, equally divided between each block. At the start of each trial, a Gabor-Flanker grid was presented and then participants had up to 2000ms to respond to each trial, after which that trial would be marked incorrect. As in Study 1, there was a gap between trials of between 500ms and 2000ms (duration randomised). A hypothesis probe was included at the end.

3.4 Analysis

As in Study 1, we calculated a composite performance score (accuracy divided by mean reaction time for correct trials) for each participant in each condition. Two-way repeated

---

[8] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Experiment

measures ANOVAs were used to analyse the effect of the two flanker conditions (speed and direction) on composite performance. The composite performance measure was used due to the different accuracy rates between conditions. To examine possible confounds, a second 2x2 repeated measures ANOVA tested for the effect of target speed (the speed of the central Gabor patch) against the flanker effect of speed (the difference between the speed of the central Gabor patch and that of the flanker Gabor patches). Results were processed in Python; statistical tests were conducted using Pingouin (Vallat, 2018), and figures were produced with Seaborn (Waskom, 2021). The data and script for analyses may be found in Supplementary Online Materials[9].

3.5 Results

Descriptive statistics for all conditions may be found in Table 3. Initial analysis revealed that five participants scored below chance level (50% accuracy) on at least one condition in at least one block. In all cases these were in either the SC-DI or SI-DI condition. As with Study 1, any scores greater than 2.5 standard deviations from the mean could be considered outliers, although in the preregistration for Study 2 we decided not to automatically remove these outliers but to analyse the data both with and without them. This prevents the unnecessary removal of variance from the sample, particularly since the outliers in Study 1 were predominantly in one condition. The analysis presented here includes the complete dataset, but the analysis excluding outliers can be recreated from the code in Supplementary Online Materials[10].

Performance scores were calculated in the same manner as Study 1. A two-way repeated-measures ANOVA was conducted to examine condition-wise effects on performance.

---

[9] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Analysis

[10] https://github.com/Social-Body-Lab/fluency-through-synchrony/tree/main/Study1/Study1_Analysis

The assumption of sphericity was met, as both the speed and direction factors only had two levels (congruent and incongruent). Both factors also met the assumption of equal variances (direction: $W = 0.514$, $p = .473$; speed: $W = 2.247$, $p = .134$). Significant main effects were found for speed and on the interaction between factors, but not for direction (see Table 4 and Figure 6). Post-hoc analysis with Bonferroni corrected t-tests revealed significantly better performance in the speed-congruent (SC) trials, compared with speed-incongruent (SI) trials, $t(81) = 3.612$, $p < .001$. Furthermore, an interaction effect between direction and speed was observed, such that the effect of speed was more pronounced in the direction-congruent (DC) than the direction-incongruent (DI) trials. Post-hoc analysis found that performance was significantly higher in DC-SC compared with DC-SI, $t(829) = 3.858$, $p < .001$.

Table 3. *Descriptive Statistics for mean reaction time, accuracy and performance across all conditions on both congruency factors and for speed of target.*

		Reaction Time (ms)		Accuracy (%)		Performance (%/ms)	
Condition		*M*	*SD*	*M*	*SD*	*M*	*SD*
Speed	Congruent	589.2	124.1	96.88	9.946	17.07	3.511
	Incongruent	602.0	141.3	97.00	8.984	16.86	3.611
Direction	Congruent	599.4	135.8	97.48	6.994	16.95	3.423
	Incongruent	591.7	130.2	96.39	11.43	16.98	3.700
Target	Faster	570.2	117.8	97.32	9.181	17.69	3.489
	Slower	621.1	142.4	96.56	9.752	16.24	3.488

Table 4. *Results of two-way repeated-measures ANOVA of speed and direction factors on performance scores.*

Factor	*df*	*F*	*p*	η_p^2
Speed	1, 81	13.05	<.001	0.139
Direction	1, 81	0.430	.514	0.005
Speed * Direction	1, 81	6.400	.008	0.073

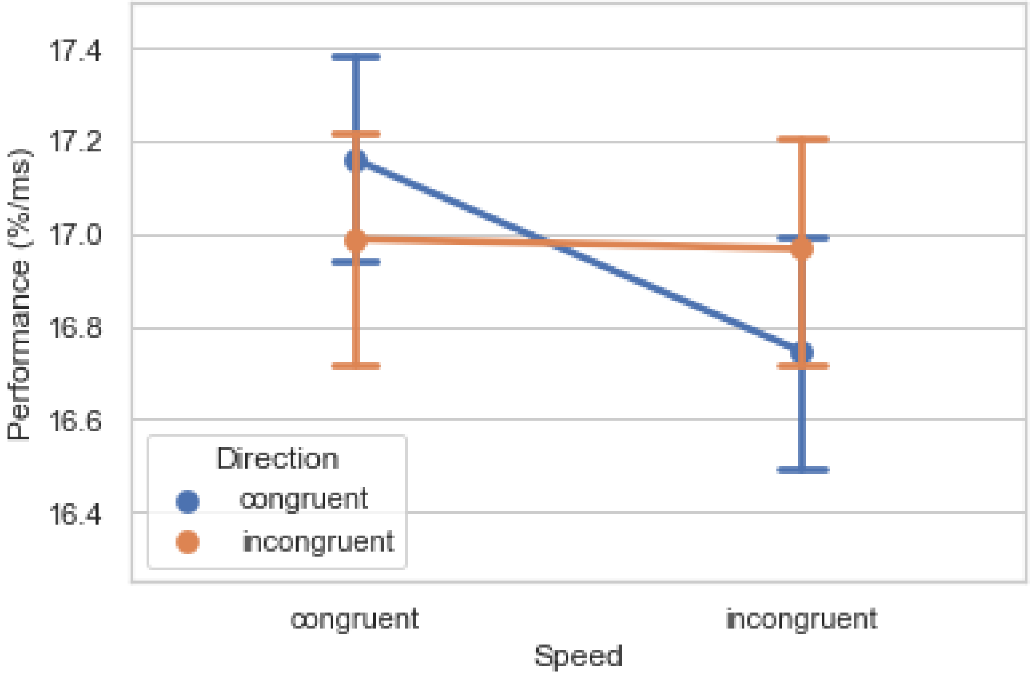


Figure 6. Interaction between the speed and direction flanker conditions. Error bars show 95% confidence intervals.

A further repeated-measures ANOVA was conducted between speed congruency (SC vs SI) and the speed level (fast vs slow) of the target Gabor patch. This was an exploratory analysis, to test for a possible confound between these two factors, and had no preregistered hypothesis. The assumptions of sphericity and equality of variances were met (target speed: $W = 0.514$, $p = .473$; speed congruency: $W = 2.247$, $p = .134$). Significant independent effects were found in both target speed and speed congruency (see Table 5). Post hoc analyses found performance to be significantly higher when the target was fast compared with slow, $t(81) = 17.74$, $p < .001$, and when speed was congruent compared with incongruent, $t(81) = 3.275$, $p < .001$. An interaction effect was also observed within the slow trials, with performance being higher in the slow-SC condition compared with the slow-SI condition, $t(81) = 5.859$, $p < .001$. No such effect was observed within the fast condition, $t(81) = -2.184$, $p = .063$ (see Figure 7).

Table 5. *Results of two-way repeated-measures ANOVA of speed and direction factors on performance scores.*

Factor	*df*	*F*	*p*	η_p^2
Speed Congruency	1, 81	10.73	<.001	0.117
Target Speed	1, 81	314.7	<.001	0.795
Congruency * Target	1, 81	31.59	<.001	0.281

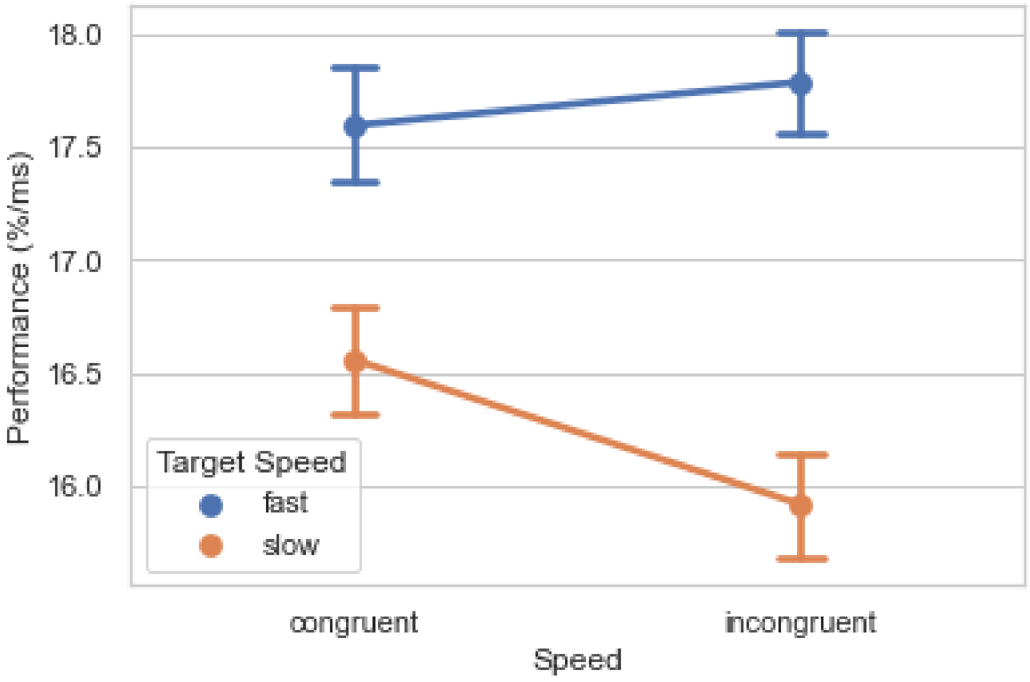


Figure 7. Interaction between target speed and speed congruency. Error bars show 95% confidence intervals.

3.6 Discussion

Study 2 was designed to replicate and extend the findings of Study 1 by including two flanker conditions: speed and direction. In each trial the target stimulus moved either in the same or different direction and either at the same speed, faster or slower than the flanker stimuli. As with Study 1, although there was a small number of participants who had severely reduced accuracy in the direction-incongruent conditions, no effect of direction-congruency was detected on overall performance. Analyses revealed a significant effect of speed on performance. Task performance was lower when the flankers were moving at a different speed to the target. Although only a relatively small increase in reaction time was observed due to incongruent speed, when combined with error rate in the overall performance score this became a moderately large effect. This suggests that differences in speed between two stimuli may influence perception of those stimuli, making them more difficult to process, consistent with our account that synchrony is associated with processing fluency. Further investigation found that this reduced performance for a speed-incongruent flanker trial was stronger in the trials that were also direction-congruent. Temporal synchrony, as occurs in the speed-congruent condition, can be used as a grouping cue (Rideaux et al., 2016). When the flankers are moving in the opposite direction to the target this may make the target more salient, creating a stronger figure-ground contrast (Wertheimer, 1938). The greater contrast between the target stimulus and the background may then make the target easier to perceive (Kornmeier & Bach, 2012). If the decrease in performance on speed-incongruent trials is due to ambiguity between the target and flankers, then adding an additional direction-incongruence may serve to ameliorate that ambiguity, making the target easier to perceive.

To check for any possible confounds, the speed of the target was examined. There was an independent effect of the target's speed relative to the flankers, with participants performing worse on slower (vs faster) trials. However, an interaction effect was also observed, showing a greater performance decrease when the target was slower in incongruent trials than in congruent trials. Nothdurft (2002) found that, when stimuli are moving at different speeds, faster motion is more salient – more readily capturing visual attention. Therefore, when the flankers are moving faster than the target, they provide a greater distraction, and performance is negatively impacted.

From this study, it appears that incongruent movement between non-periodic stimuli may be more difficult to perceive than congruent movement, but particularly when the target was slower than distractor stimuli. The faster stimulus may be more salient (Nothdurft, 2002), thus extra effort is required to direct attention towards a slower target. As in Study 1, there was no effect of direction in Study 2. The different effects of speed and direction in Study 2 may be pertinent when considering the implications of these results for the perception of periodic synchrony.

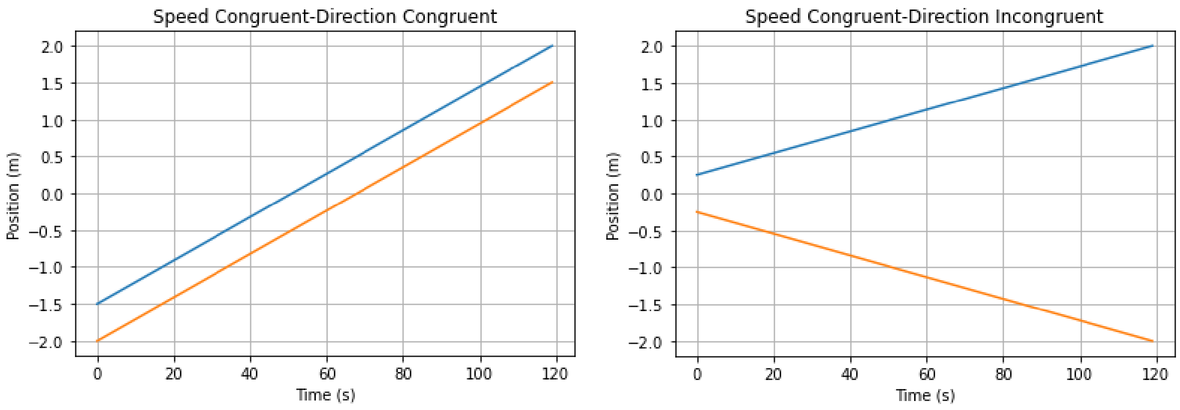
4 General Discussion

Taken together, these experiments represent an important step towards establishing processing fluency as a potential factor in the perception of synchrony. Here we demonstrate that non-synchrony may reduce performance on a Flanker task using animated stimuli moving at different rates, but not in different directions. This is in contrast with Malecki and Treue (2012), although their stimuli used moving dots rather than animated Gabor patches. It may be that movement direction was easier to detect in the Gabor patches, reducing the effect of direction incongruency. It should also be noted that Malecki and Treue (2012) did not include a speed manipulation, so a direct comparison cannot be made with Study 2. Future studies could compare more directly between these different types of animated Flanker tasks.

The stimuli used here are very abstract, compared with most of the literature studying synchrony in social contexts (Mogan et al., 2017; Rennung & Göritz, 2016; Vicaria & Dickens, 2016). This task was chosen because it provides continuous movement which may be in synchrony without being rhythmic, as a strongly rhythmic stimulus could encourage participants to entrain their responses to the stimulus (Killingly et al., 2021), thus influencing reaction times and confounding the results. The animated Gabor patch provides a solution, as it has a continuous movement without providing a “beat” that participants could tap in time with. Although this makes it difficult to apply the findings from the present study to real-world social contexts, it does establish a precedent for studying reaction times in synchrony perception studies.

Two dimensions of coordination were used in the present study. Direction-congruency could be thought of “behaviour matching”, while speed-congruency could be “synchrony” using Bernieri and Rosenthal’s (1991) terminology. Behaviour matching (imitation) occurs when actions are matched in kind, while synchrony involves actions to occur simultaneously in time (Bernieri & Rosenthal, 1991), although many studies involve behavioural synchrony in which actions are matched in both time and kind. However, this may be overly simplistic as, in naturalistic interpersonal coordination, movements often contain periodic reversals (rapid changes in acceleration) associated with the beat or tactus (Burger et al., 2014). Non-synchrony in social contexts could contain differences in both speed and direction at varying times, although synchrony should involve speed and direction being matched at every timepoint.

The stimuli used in this study may be best understood as derivatives of periodic movement. They are continuous vectors, moving at a consistent velocity. As such, the conditions used in Study 2 may be plotted as linear functions (Figure 8).



(a)

(b)

(c)

(d)

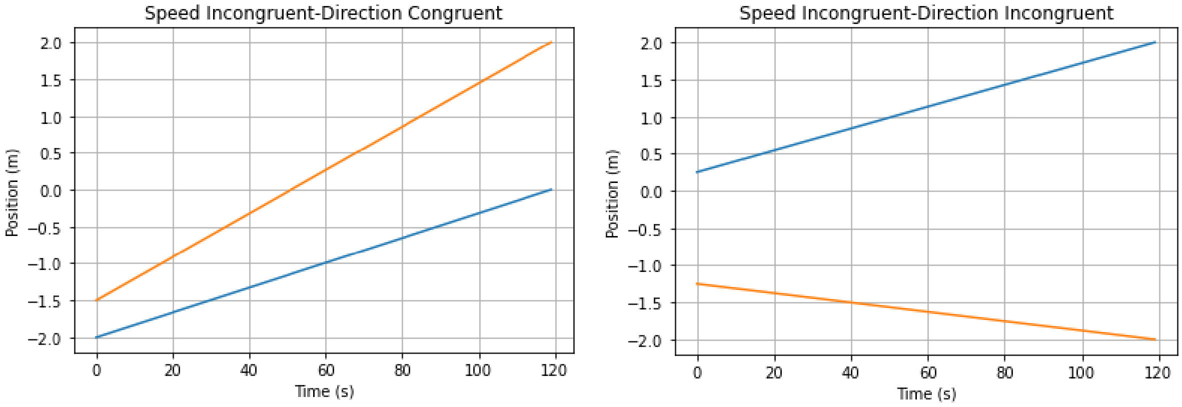


Figure 8. The conditions from Study 2 (blue representing the target and orange representing the flankers), plotted as linear functions showing change in position over time.

Synchronised, periodic movement emerges when two oscillators share the same frequency (Repp, 2005), such as in Figure 9a. The derivative of any timepoint in Figure 9a will always result in two parallel lines, as in Figure 8a. Therefore, the experience of perceiving the SC-DC condition resembles the experience of perceiving synchronised, periodic movement for a brief moment.

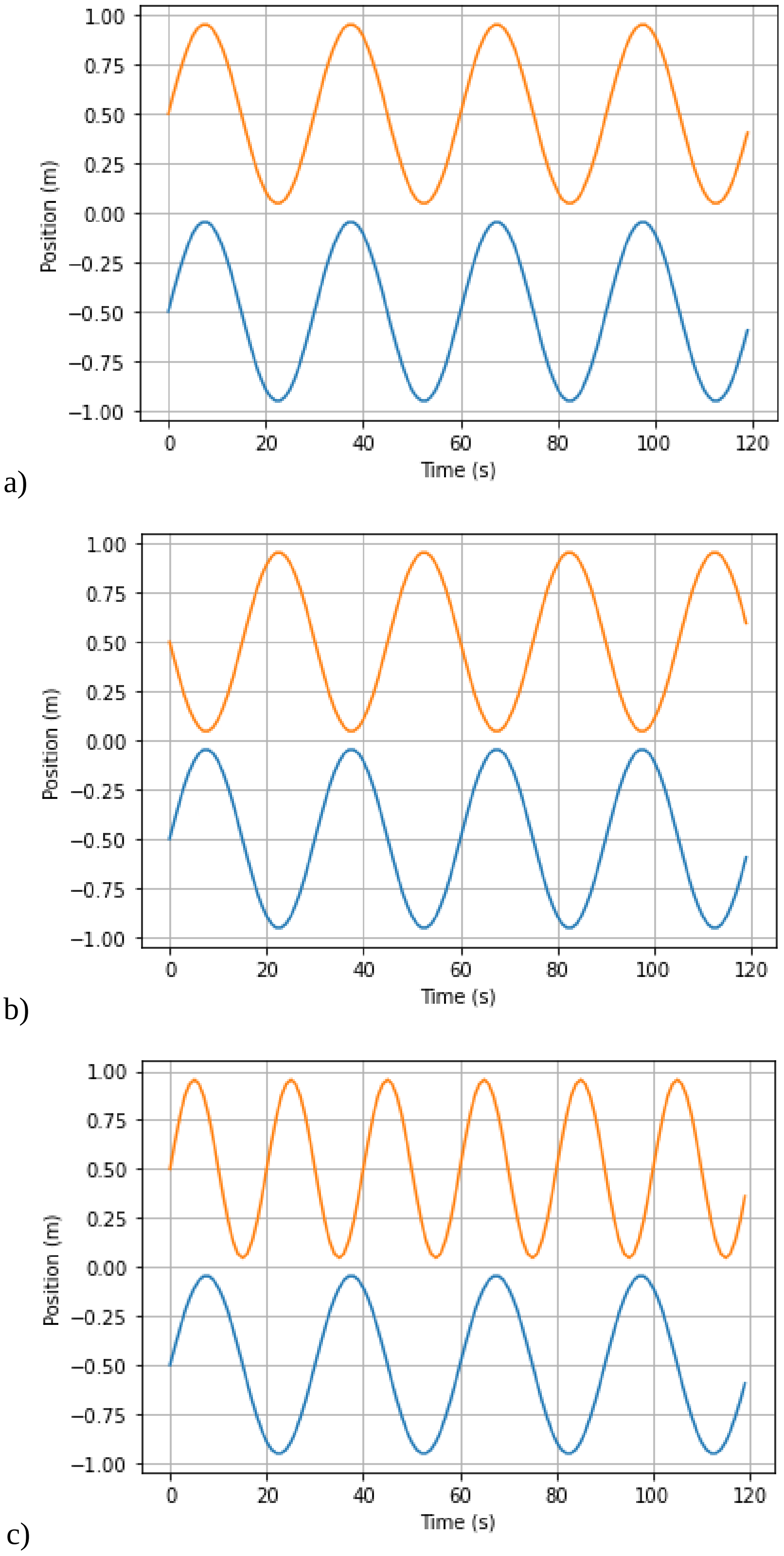


Figure 9. Illustration of two oscillators (one in blue, the other in orange) moving over time in: (a) synchrony, (b) anti-phase synchrony, (c) non-synchrony.

However, two sine waves that are offset by half their period may still be considered synchronised, i.e. in an anti-phase relationship (Repp, 2005). A common example of this would be two hands clapping. Although the hands will always be moving in opposite directions, they would, nevertheless, be synchronised. Such a relationship may be seen in Figure 9b. The derivatives of these waves at any timepoint would always result in two vectors of equal but opposite slopes (except at the peaks and troughs), such as seen in Figure 8b, and corresponding to the SC-DI condition. Therefore, direction incongruency, without speed incongruency (as in our Study 1), is likely to emerge in the moment-to-moment perception of anti-phase synchrony.

Truly non-synchronised stimuli will rarely have speed congruency. The derivative of the waves in Figure 9c will, at any given timepoint, likely resemble the vectors in Figure 8c or Figure 8d – corresponding to the speed incongruent conditions. The only exception would be rare moments when the peaks and troughs may align. Therefore, the speed incongruent condition in Study 2 may best capture the experience of a single moment of non-synchrony in periodic movement.

The stimuli we have used here may be best understood as derivatives of synchronised movement. The reduced performance observed in speed-incongruent (SI) trials in Study 2 indicates a higher processing load. If the SI condition is best understood as a snapshot of non-synchrony (Figure 9c), then this suggests higher processing load when observing non-synchrony. Conversely, SC conditions arise at every time-point during synchronised interaction (whether in-phase or anti-phase).

We suggest that speed congruency – a feature of periodic synchrony – is easier to process. Previous studies have found that Gabor patches moving at the same rate are more likely to be grouped together (Rideaux et al., 2016). The ease of processing observed here may arise from this grouping effect. This finding provides an extension of our understanding of the perceptual experience of synchrony at single time-points, rather than just as a continuous experience.

As a further exploratory analysis, we found that performance was worse when the target was slower than the flankers.. This is likely because fast motion may more easily capture our attention (Nothdurft, 2002), making those flanker stimuli more distracting. It should also be noted that when the target stimulus moved in the opposite direction to the flankers, this appeared to greatly decrease accuracy in some participants. This affected a small number of participants in both experiments; in Study 1 they were removed as statistical outliers but they were retained in Study 2. Some participants also self-reported that direction-incongruency felt particularly difficult, and one participant reported perceiving the stimuli as rotating, rather than moving. Further investigation would be required to understand how the stimuli gave rise to this perceptual experience. Prior research has used scrolling vertical lines to induce a sense of rotation in participants (Zacharias & Young, 1981). However, the static Gabor patches were included in this study precisely to avoid such occurrences. Lange-Malecki and Treue (2012) did not report any individual differences within their sample, although they did find decreased performance on average for direction-incongruency using a similar animated Flanker design to that presented here. These observations provide much scope for further investigation with these stimuli.

Most studies into the synchrony-bonding effect have involved participatory synchrony. Our participants were not required to move or tap in time with the stimuli, only to respond by categorising stimuli. This makes it difficult to compare to previous work, like that of Hove and Risen (2009), but it did remove potential confounds that could arise from measuring reaction times while participants perform rhythmic actions (Killingly et al., 2021). Nevertheless, some previous studies have found that perception of synchrony can lead to a greater perception of beauty and more enjoyment, when observing others performing joint action (McEllin et al., 2020). This is consistent with the effects one would expect if viewers were experiencing processing fluency from a stimulus (Reber et al., 1998). The results here warrant further research into processing fluency effects arising from the perception of synchrony.

Future research is required to investigate the role of processing fluency in synchrony perception. Although our results suggest that non-synchrony may be more difficult to perceive than synchrony, future studies could target different stages in perceptual processing and executive function to examine how synchrony is processed. New tasks may need to be developed to target different stages of processing. Furthermore, rhythmic stimuli in both the visual and auditory domains should also be studied, as most naturalistic synchronised movement involves rhythmic entrainment, as well as sensorimotor synchronisation across multiple sensory modalities (McNeill, 1997), rather than continuous visual motion as presented here. Finally, although this study suggests synchrony is easier to perceive than non-synchrony, it did not test whether synchrony is easier to participate in, nor did it test for any affective or social consequences of the synchrony. To establish processing fluency as a possible factor in the synchrony-bonding effect, further investigation is required.

Most of the theories attempting to account for the social bonding effects of synchrony rely upon higher-order social cognition (Mogan et al., 2017), and the low-level perceptual processes involved have been ignored. However, this study suggests a role of early-stage perceptual processing in the synchrony-bonding effect, at least for the visual domain. In particular, it suggests that synchronised movement may be easier to process than non-synchronised movement, and that this may occur in non-social stimuli. This does not preclude other levels of explanation, and there may be interactions between different levels of cognition. Other contextual factors may influence the way synchrony is perceived or motivated (Miles et al., 2010). This study only suggests that synchrony is easier to perceive, but how that ease of perception is interpreted may vary with other factors.

The present study represents a first attempt to apply the processing fluency theory to the perception of synchronised action in a non-social setting and there is much scope to expand upon these findings. We tested the novel hypothesis that synchrony is easier to perceive than non-synchrony. We suggest that an experience of processing fluency may arise from the ease of organising (or grouping) synchronous stimuli. Based upon the observation that performance is most affected by distractors that move faster than the target, the disfluency may also occur from attention control. The stimuli presented here may be best understood as "snapshots" of synchrony, as they are continuous vectors without the periodic movement usually associated with synchronisation between oscillators. As such, we demonstrate that when objects move at the same speed (but not necessarily in the same direction), they may be easier to process. This state of speed-congruency is a feature of both in-phase and anti-phase synchrony, but rarely occurs when oscillators have different frequencies. While the present study does suggest a role for processing fluency in the perception of synchronised action, it does not demonstrate that the same would exist when actively participating in synchrony, or that the experience of processing fluency would necessarily lead to positive social evaluations. Further investigation is required to gain a better understanding of the role that low-level perceptual processing plays in the synchrony-bonding effect.

5 References

Amano, K., Edwards, M., Badcock, D. R., & Nishida, S. (2009). Adaptive pooling of visual motion signals by the human visual system revealed with a novel multi-element stimulus. *Journal of Vision*, *9*(3), 4–4. https://doi.org/10.1167/9.3.4

Bamford, J. S., Burger, B., & Toiviainen, P. (2016). Are we dancing to the same beat? empathy and interpersonal synchronisation in the silent disco. In B. Burger, J. S. Bamford, & E. Carlson (Eds.), *The 9th International Conference of Students of Systematic Musicology (SysMus16): Programme, Abstracts & Proceedings* (Issue June). University of Jyväskylä.

Bernieri, F. J., & Rosenthal, R. (1991). Interpersonal coordination: Behavior matching and interactional synchrony. In R. S. Feldman & B. Rimé (Eds.), *Fundamentals of nonverbal behavior* (Issue February, pp. 401–432). Cambridge University Press. https://psycnet.apa.org/record/1991-98576-011

Bispham, J. C. (2018). *Music's Evolutionary 'Design Features'* [Doctoral]. University of Cambridge.

Bregman, A. S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequences of tones. *Journal of Experimental Psychology*, *89*(2), 244–249. https://doi.org/10.1037/h0031163

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S. H., & Toiviainen, P. (2014). Hunting for the beat in the body: On period and phase locking in music-induced movement. *Frontiers in Human Neuroscience*, *8*(November), 1–16. https://doi.org/10.3389/fnhum.2014.00903

Chen, A., Tang, D., & Chen, X. (2013). Training Reveals the Sources of Stroop and Flanker Interference Effects. *PLoS ONE*, *8*(10). https://doi.org/10.1371/journal.pone.0076580

Cirelli, L. K., Einarson, K. M., & Trainor, L. J. (2014). Interpersonal synchrony increases prosocial behavior in infants. *Developmental Science*, *17*(6), 1003–1011. https://doi.org/10.1111/desc.12193

Clark, A. (2015). Embodied Prediction. *Open MIND*, *7*, 1-21. https://doi.org/10.15502/9783958570115

Crump, M. J. C., McDonnell, J. V., & Gureckis, T. M. (2013). Evaluating Amazon's Mechanical Turk as a Tool for Experimental Behavioral Research. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0057410

de Leeuw, J. R. (2015). jsPsych: A JavaScript library for creating behavioral experiments in a Web browser. *Behavior Research Methods*, *47*(1), 1–12. https://doi.org/10.3758/s13428-014-0458-y

De Valois, R. L., & De Valois, K. K. (1991). Vernier acuity with stationary moving Gabors. *Vision Research*, *31*(9), 1619–1626. https://doi.org/10.1016/0042-6989(91)90138-U

Demos, A. P., Chaffin, R., Begosh, K. T., Daniels, J. R., & Marsh, K. L. (2012). Rocking to the beat: Effects of music and partner's movements on spontaneous interpersonal coordination. *Journal of Experimental Psychology: General*, *141*(1), 49–53. https://doi.org/10.1037/a0023843

Dolležal, L.-V., Brechmann, A., Deike, S., & Klump, G. M. (2014). Evaluating auditory stream segregation of SAM tone sequences by subjective and objective psychoacoustical tasks, and brain activity. *Frontiers in Neuroscience*, *8*, 119. https://doi.org/10.3389/fnins.2014.00119

Dutilh, G., Wagenmakers, E.-J., Visser, I., & Van Der Maas, H. L. J. (2011). A Phase Transition Model for the Speed-Accuracy Trade-Off in Response Time Experiments. *Cognitive Science*, *35*(2), 211–250. https://doi.org/10.1111/j.1551-6709.2010.01147.x

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149.

Fitch, W. T. (2013). Rhythmic cognition in humans and animals: distinguishing meter and pulse perception. *Frontiers in Systems Neuroscience*, *7*. https://doi.org/10.3389/fnsys.2013.00068

Friston, K. J. & Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1521), 1211-1221. https://doi.org/10.1098/rstb.2008.0300

Hove, M. J., & Risen, J. L. (2009). It’s all in the timing: Interpersonal synchrony increases affiliation. *Social Cognition*, *27*(6), 949–960. https://doi.org/10.1521/soco.2009.27.6.949

Hughes, R. W., Hurlstone, M. J., Marsh, J. E., Jones, D. M., & Vachon, F. (2013). Cognitive control of auditory distraction: Impact of task difficulty, foreknowledge, and working memory capacity supports duplex-mechanism account. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 539–553. https://doi.org/10.1037/a0029064

Hukin, R. W., & Darwin, C. J. (1995). Comparison of the effect of onset asynchrony on auditory grouping in pitch matching and vowel identification. *Perception & Psychophysics*, *57*(2), 191–196. https://doi.org/10.3758/BF03206505

Killingly, C., Lacherez, P., & Meuter, R. (2021). Singing in the brain: investigating the cognitive basis of earworms. *Music Perception*, *38*(5), 456–472. https://doi.org/10.1525/mp.2021.38.5.456

Kornmeier, J., & Bach, M. (2012). Ambiguous figures - what happens in the brain when perception changes but not the stimulus. *Frontiers in Human Neuroscience*, *6*(MARCH 2012), 1–23. https://doi.org/10.3389/fnhum.2012.00051

Lange-Malecki, B., & Treue, S. (2012). A flanker effect for moving visual stimuli. *Vision Research*, *62*, 134–138. https://doi.org/10.1016/j.visres.2012.03.016

Leder, H. (2013). Next steps in neuroaesthetics: Which processes and processing stages to study? *Psychology of Aesthetics, Creativity, and the Arts*, *7*(1), 27–37. https://doi.org/10.1037/a0031585

Lee, H., Launay, J., & Stewart, L. (2020). Signals through music and dance: Perceived social bonds and formidability on collective movement. *Acta Psychologica*, *208*(June), 103093. https://doi.org/10.1016/j.actpsy.2020.103093

Lick, D. J., & Johnson, K. L. (2015). The Interpersonal Consequences of Processing Ease: Fluency as a Metacognitive Foundation for Prejudice. *Current Directions in Psychological Science*, *24*(2), 143–148. https://doi.org/10.1177/0963721414558116

Makin, A. D. J., Pecchinenda, A., & Bertamini, M. (2012). Implicit affective evaluation of visual symmetry. *Emotion*, *12*(5), 1021–1030. https://doi.org/10.1037/a0026924

McEllin, L., Knoblich, G., & Sebanz, N. (2020). Synchronicities that shape the perception of joint action. *Scientific Reports*, *10*(1), 1–10. https://doi.org/10.1038/s41598-020-72729-6

McNeill, W. H. (1997). *Keeping Together in Time: Dance and Drill in Human History*. Harvard University Press.

Miles, L. K., Griffiths, J. L., Richardson, M. J., & Macrae, C. N. (2010). Too late to coordinate: contextual influences on behavioral synchrony. *European Journal of Social Psychology*, *40*, 52–60. https://doi.org/10.1002/ejsp.721

Mogan, R., Fischer, R., & Bulbulia, J. A. (2017). To be in synchrony or not? A meta-analysis of synchrony's effects on behavior, perception, cognition and affect. *Journal of Experimental Social Psychology*, *72*(October), 13–20. https://doi.org/10.1016/j.jesp.2017.03.009

Nothdurft, H. C. (2002). Attention shifts to salient targets. *Vision Research*, *42*(10), 1287–1306. https://doi.org/10.1016/S0042-6989(02)00016-0

Pinet, S., Zielinski, C., Mathôt, S., Dufau, S., Alario, F. X., & Longcamp, M. (2017). Measuring sequences of keystrokes with jsPsych: Reliability of response times and interkeystroke intervals. *Behavior Research Methods*, *49*(3), 1163–1176. https://doi.org/10.3758/s13428-016-0776-3

Polak, R., Jacoby, N., Fischinger, T., Goldberg, D., Holzapfel, A., & London, J. (2018). Rhythmic prototypes across cultures: A comparative study of tapping synchronisation. *Music Perception*, *36*(1), 1–23. https://doi.org/10.1525/MP.2018.36.1.1

Pressnitzer, D., Suied, C., & Shamma, S. A. (2011). Auditory scene analysis: the sweet music of ambiguity. *Frontiers in Human Neuroscience*, *5*(December), 1–11. https://doi.org/10.3389/fnhum.2011.00158

Purves, D., Paydarfar, J. A., & Andrews, T. J. (1996). The wagon wheel illusion in movies and reality. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(8), 3693–3697. https://doi.org/10.1073/pnas.93.8.3693

Rao, R. P. N. & Ballard, D. H. (1999). Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience, 2*(1), 79-87. https://doi.org/10.1038/4580

Reber, R., & Schwarz, N. (1999). Effects of Perceptual Fluency on Judgments of Truth. *Consciousness and Cognition*, *8*(3), 338–342. https://doi.org/10.1006/ccog.1999.0386

Reber, R., Schwarz, N., & Winkielman, P. (2004). Processing fluency and aesthetic pleasure: is beauty in the perceiver's processing experience? *Personality and Social Psychology Review*, *8*(4), 364–382.

Reber, R., Winkielman, P., & Schwarz, N. (1998). Effects of Perceptual Fluency on Affective Judgments. *Psychological Science*, *9*(1), 45–48. https://doi.org/10.1111/1467-9280.00008

Reddish, P., Fischer, R., & Bulbulia, J. (2013). Let's Dance Together: Synchrony, Shared Intentionality and Cooperation. *PLoS ONE*, *8*(8). https://doi.org/10.1371/journal.pone.0071182

Rennung, M., & Göritz, A. S. (2016). Prosocial Consequences of Interpersonal Synchrony. *Zeitschrift Für Psychologie*, *224*(3), 168–189. https://doi.org/10.1027/2151-2604/a000252

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review*, *12*(6), 969–992. https://doi.org/10.3758/BF03206433

Rideaux, R., Badcock, D. R., Johnston, A., & Edwards, M. (2016). Temporal synchrony is an effective cue for grouping and segmentation in the absence of form cues. *Journal of Vision*, *16*(11), 23. https://doi.org/10.1167/16.11.23

Savage, P. E., Loui, P., Tarr, B., Schachner, A., Glowacki, L., Mithen, S., & Fitch, W. T. (2021). Music as a coevolved system for social bonding. *Behavioral and Brain Sciences*, *44*, 1–22. https://doi.org/10.1017/S0140525X20000333

Schwarz, N. (2012). Feelings-as-Information Theory. In *Handbook of Theories of Social Psychology* (Issue January, pp. 289–308). SAGE Publications Ltd. https://doi.org/10.4135/9781446249215.n15

Valdesolo, P., & DeSteno, D. (2011). Synchrony and the social tuning of compassion. *Emotion*, *11*(2), 262–266. https://doi.org/10.1037/a0021302

Vallat, R. (2018). Pingouin: statistics in Python. *Journal of Open Source Software, 3*(31), 1026. https://doi.org/10.21105/joss.01026

Vicaria, I. M., & Dickens, L. (2016). Meta-Analyses of the Intra- and Interpersonal Outcomes of Interpersonal Coordination. *Journal of Nonverbal Behavior*, *40*(4), 335–361. https://doi.org/10.1007/s10919-016-0238-8

Vicary, S., Sperling, M., Von Zimmermann, J., Richardson, D. C., & Orgs, G. (2017). Joint action aesthetics. *PLoS ONE*, *12*(7), 1–21. https://doi.org/10.1371/journal.pone.0180101

Waskom, M. (2021). Seaborn: Statistical Data Visualization. *Journal of Open Source Software*, *6*(60), 3021. https://doi.org/10.21105/joss.03021

Wertheimer, M. (1938). Laws of Organisation in Perceptual Forms. In W. Ellis (Ed.), *A source book of Gestalt psychology* (pp. 71–88). Routledge & Kegan Paul. http://www.sapili.org/subir-depois/en/ps000200.pdf

Wheatley, T., & Sievers, B. (2016). Toward a neuroscience of social resonance. In J. D. Greene, I. Morrison, & M. E. P. Seligman (Eds.), *Positive Neuroscience* (pp. 37–54). Oxford University Press.

Winkielman, P., & Cacioppo, J. T. (2001). Mind at ease puts a smile on the face: Psychophysiological evidence that processing facilitation elicits positive affect. *Journal of Personality and Social Psychology*, *81*(6), 989–1000. https://doi.org/10.1037/0022-3514.81.6.989

Winkielman, P., Schwarz, N., Fazendeiro, T. A., & Reber, R. (2003). The hedonic marking of processing fluency: Implications for evaluative judgement. In *The Psychology of Evaluation: Affective Processes in Cognition and Emotion*.

Woolhouse, M. H., Tidhar, D., & Cross, I. (2016). Effects on Inter-Personal Memory of Dancing in Time with Others. *Frontiers in Psychology*, *7*(February), 1–8. https://doi.org/10.3389/fpsyg.2016.00167

Zacharias, G. L., & Young, L. R. (1981). Influence of combined visual and vestibular cues on human perception and control of horizontal rotation. *Experimental Brain Research, 41*(2), 159–171. https://doi.org/10.1007/BF00236605

Zeamer, C., & Fox Tree, J. E. (2013). The process of auditory distraction: Disrupted attention and impaired recall in a simulated lecture environment. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(5), 1463–1472. https://doi.org/10.1037/a0032190

Zelechowska, A., Sanchez, V. G., & Jensenius, A. R. (2020). Standstill to the ‘beat’. *Proceedings of the 15th International Conference on Audio Mostly*, 107–113. https://doi.org/10.1145/3411109.3411139