

# Time perception in human movement: Effects of speed and agency on duration estimation

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## Abstract

While the effects of synthesised visual stimuli on time perception processes are well documented, very little research on time estimation in human movement stimuli exists. This study investigated the effects of movement speed and agency on duration estimation of human motion. Participants were recorded using optical motion capture while they performed dance-like movements at three different speeds. They later returned for a perceptual experiment in which they watched point-light displays of themselves and one other participant. Participants were asked to identify themselves, to estimate the duration of the recordings, and to rate expressivity and quality of the movements. Results indicate that speed of movement affected duration estimations such that faster speeds were rated longer, in accordance with previous findings in non-biological motion. The biasing effects of speed were stronger for watching others' movements than for watching one's own point-light movements. Duration estimations were longer after acting out the movement compared with watching it, and speed differentially affected ratings of expressivity and quality. Findings suggest that aspects of temporal processing of visual stimuli may be modulated by inner motor representations of previously performed movements, and by physically carrying out an action compared with just watching it. Results also support the inner clock and change theories of time perception for the processing of human motion stimuli, which can inform the temporal mechanisms of the hypothesised separate processor for human movement information.

## Keywords

Self–other identification; biological motion; point-light displays; time estimation; motion capture; dance-like movement

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## Introduction

Experiences of time differ fundamentally depending on our activities, inner states, and the information we perceive and process. While illusions of time perception have been extensively researched in the context of highly controlled, synthesised visual and audio stimuli, less research exists on timing mechanisms in more naturalistic stimuli, particularly human motion. Furthermore, investigating time perception in human motion opens up new questions about human cognition such as how processes of estimating time might intertwine with self-recognition mechanisms, and how passing time might be perceived differently when carrying out an action compared with when watching an action. The current study draws these issues together in a novel approach to duration estimation and self-recognition from naturalistic dance-like movements.

## Time perception

Human perception of time is central to the psychological research of conscious experience. Time fundamentally shapes our experience of the world around us (Wittmann, 2016), and distortions of time perception have been found to be related to pathological conditions such as schizophrenia, Parkinson's disease, and attention deficit disorders (Grondin, 2010). Despite this, the cognitive and neural mechanisms of human time perception remain largely unknown and debated (Teki, 2016; Wittmann, 1999). One

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influential model of time perception is that of the internal clock (Treisman, 1963; Wang & Wöllner, 2019), which proposes that humans possess an inner pacemaker that keeps track of time through the accumulation of pulses. It is proposed that this internal clock can be sped up or slowed down through arousal mechanisms, which in turn affect time perception by altering the number of pulses accumulated in a given period (Droit-Volet et al., 2013). Complementing this inner clock theory is the “attentional gate model” (Zakay & Block, 1995), which proposes that when attention is directed towards passing time, the “attentional gate” opens wider allowing more pulses to be accumulated and causing durations to be overestimated.

Regardless of which theoretical model is used to understand time, one finding has been consistently observed in empirical studies: human perception of time is malleable and prone to distortion. For example, time spent doing nothing seems to last longer than durations that are filled with a task (Weybrew, 1984). Furthermore, duration estimations can be influenced by the spatial location of stimuli sources (Grondin, 2010), familiarity with stimuli (Block et al., 2010), the sensory modality of stimuli (Droit-Volet et al., 2007), and our emotional state (Droit-Volet et al., 2013). Duration estimation has also been shown to be modulated by expertise in particular spatial-temporal skills such as musicianship (Panagiotidi & Samartzi, 2013) and dance (Sgouramani & Vatakis, 2014).

### *The effect of speed on time perception*

There is a solid evidence base that the speed of stimuli tends to affect perceived time such that faster speeds lead to longer duration estimations. For example, this has been shown with musical tempo (Droit-Volet et al., 2013; Oakes, 2003; Panagiotidi & Samartzi, 2013), a driving simulator (Leiser et al., 1991), rotating patterns of spots (Tayama et al., 1987), moving shapes (Brown, 1995), and both visual and tactile observations of a spinning wheel (Tomassini et al., 2011). Furthermore, we have found in previous studies that tapping along to lower metrical levels (i.e., faster tapping) results in shorter duration estimations (Hammerschmidt & Wöllner, 2020), and slow motion film scenes have been shown to be rated relatively shorter than real-time scenes (Wöllner et al., 2018).

Differing theories exist on the reason for these effects of speed on duration estimation. In one view, it is theorised that exposure to fast tempi speeds up the internal clock via arousal mechanisms, causing more pulses to be accumulated and therefore durations to be overestimated (Droit-Volet et al., 2013; Treisman et al., 1990). This speeding-up of the internal clock is also shown to be triggered by repetitive clicks, visual flicker, white noise, and expanding circles (Ortega & López, 2008; Treisman et al., 1990; Wearden et al., 2017). Taking another perspective, it is suggested that duration estimation is based on the number

of changing events perceived (Brown, 1995; Lhamon & Goldstone, 1975). Fast moving stimuli involve a high rate of change in visual information, and thus stretch our perception of time. Regardless of the underlying cause, the two theories predict the same effect of speed on duration estimation: faster stimuli that include more events lead to longer estimations of time.

However, an alternative account of the effects of speed on time perception exists. According to some studies on visual searching behaviour, faster moving stimuli are more attention-grabbing than slow ones (e.g., Ivry & Cohen, 1992). Thus, fast stimuli would be expected to narrow the attentional gate causing fewer pulses to be accumulated and time to be underestimated. Indeed, this effect was found for video stimuli of ballet steps (Sgouramani & Vatakis, 2014). Importantly, this study held the number of repetitions (i.e., temporal frequency) constant, so that only the effects of velocity were examined. Thus, according to the attentional gate account, when temporal frequency is held constant, stimuli displaying higher velocity should result in shorter duration estimations. In addition, research on apparent human motion from static images has shown that when apparent motion is perceived as faster due to longer implied movement paths, perceptions of time dilate (Orgs et al., 2011). Thus, there may be different effects of temporal frequency and motion velocity on duration estimation.

### *Time perception in biological motion*

Duration estimation processes may also be influenced by the kind of stimuli used in perceptual studies. Despite the ubiquity of the temporal processing of biological, human motion in our everyday lives, surprisingly few studies exist on the perception of time for biological motion stimuli. Nonetheless, evidence that human motion information can influence temporal processing is exemplified by London et al. (2016), who found that music paired with more vigorous dance movement caused tempo to be perceived as faster. Furthermore, it has been shown that learning for tasks based on human movement information is differentially affected by cognitive load compared with that involving non-human movement information (Wong et al., 2009). This finding supports the idea that general cognitive processing for human movement may take place differently than for other kinds of movement. Wong et al. (2009) propose that there may be a separate working memory processor for human motion, which allows us to easily process information high in cognitive load. Memory processes and cognitive load are important parts of current models of time perception (Block et al., 2010; Droit-Volet et al., 2007; Ortega & López, 2008; Wittmann, 1999), and there is some evidence for modality-specific timing mechanisms (Grondin, 2010). Therefore, if there is a separate working memory processor for human motion, there might also be timing mechanisms specific to processing human

motion information. Thus, effects on duration estimation previously observed in other kinds of stimuli may not be generalisable to human motion stimuli. Indeed, one study found that velocity affected duration estimations for non-biological motion animations, while it did not affect duration estimations for movement modelled on biological motion (Gavazzi et al., 2013). The authors suggest that estimations of time are informed by knowledge of biological motion, which fits well with the suggestion that timing mechanisms are shared between action and perception processes (Keele et al., 1985; Schütz-Bosbach & Prinz, 2007; Treisman et al., 2007; Wittmann, 1999). In addition, research suggests the existence of different neurological mechanisms of temporal control for discontinuous compared with continuous movements (Spencer et al., 2003); therefore, the continuity or rhythmicity of movements may also influence time perception processes. To our knowledge, no study has so far examined duration estimation in point-light displays (PLDs) of human motion, or how estimations may differ between time taken to perform, or time taken to watch the same action. Addressing these gaps in the literature will provide important knowledge relevant to the theory of a separate working memory processor for human movement, and different time perception mechanisms for biological motion compared with non-biological motion.

### *Self-recognition*

The human capability to recognise oneself from motion information is central to understanding the cognition of action and perception. For example, common coding theory (Prinz, 1997; Schütz-Bosbach & Prinz, 2007; Van der Wel et al., 2013) posits that cognitive representations for action and perception are overlapping, suggesting that action experience informs perception. In extension of this, the direct-matching hypothesis (Rizzolatti et al., 2001) predicts that when we perceive actions, we compare them with inner motor representations of our previously performed action repertoire (Campbell & Cunnington, 2017; Lago Rodríguez et al., 2014). When we view our own actions, our motor system “resonates,” allowing us to identify the action as our own (Dewey & Knoblich, 2016; Jeannerod, 2003).

Research in this field typically employs the PLD technique of presenting movement, which was first developed by Johansson (1973). The aim is to present motion information alone, while obscuring any potentially biasing influences. Several studies on self-recognition have indicated that people can reliably identify themselves from PLDs of walking (Beardsworth & Buckner, 1981; Cutting & Kozlowski, 1977; Sevdalis & Keller, 2010), although other studies have found evidence to the contrary (Loula et al., 2005; Wöllner, 2012). Nonetheless, successful self-other identification has been shown in many types of

action such as dancing and clapping (Sevdalis & Keller, 2010), dance-like actions (Bläsing & Sauzet, 2018), piano playing (Repp & Knoblich, 2004), conducting (Wöllner, 2012), and drawing (Knoblich & Prinz, 2001). It has further been suggested that self-recognition is easier for more complex or expressive movements, which present more idiosyncrasy (Loula et al., 2005; Sevdalis & Keller, 2010; Su & Keller, 2018). Finally, self-recognition of clapping from PLDs has been shown to remain robust with as few as two markers (Sevdalis & Keller, 2010), and self-recognition from walking has been shown to be independent of viewing angle (Jokisch et al., 2006). Very little research exists on self-recognition in highly controlled dance-like movements with limited idiosyncrasy or on the influence of the performed speed of movement on self-recognition. It is unknown, e.g., whether the motor resonance system may function better at faster, slower, or more comfortable speeds. Such knowledge will expand our understanding of self-recognition processes and thus theories of action–perception coupling.

Furthermore, based on the suggestion that the matching of observed motion to inner representations informs our estimations of passing time (Gavazzi et al., 2013), we might predict that inner motor representations of our own movements provide more accurate timing information when we watch ourselves compared with watching others. Investigating this problem will deepen our understanding of how biological motion knowledge interacts with cognitive timing mechanisms.

In summary, previous research in non-biological motion has shown that speed of visual stimuli affects duration estimations such that faster speeds result in longer estimations. However, findings in synthesised motion stimuli suggest that this effect may not apply to biological motion (Gavazzi et al., 2013), while the hypothesised separate working memory processor for human motion (Wong et al., 2009) may imply different temporal processing mechanisms for watching human movement. Effects of speed on duration estimation have yet to be studied in real human motion stimuli. Previously observed effects of speed on duration estimation are theoretically explained by both entrainment to the inner clock (Treisman, 1963) and the change theory of time (Brown, 1995), both of which predict that faster stimuli lead to longer duration estimations. Alternatively, it has been found that when temporal frequency is controlled, velocity of motion results in narrowing of the attentional gate (Zakay & Block, 1995) and thus shorter duration estimations (Sgouramani & Vatakis, 2014). This has also been shown for implied motion in static images (Orgs et al., 2011). Thus, research on the effects of speed of visual stimuli on duration estimation should consider the relative impacts of both temporal frequency (i.e., event density) and velocity of motion. The effects of agency on duration estimation are unknown, although it has been suggested that inner

motion representations may inform time perception (Gavazzi et al., 2013), so systematic variations in duration estimation due to agency could be hypothesised. Finally, while common coding theory (Prinz, 1997) and the direct-matching hypothesis (Rizzolatti et al., 2001) predict that humans can recognise themselves from motion information alone, very little research has tested self-recognition abilities in very controlled movements, and it is not known whether self-recognition may be better for certain movement speeds.

## Aims

This study aimed to expand and deepen the theoretical understanding of the cognitive mechanisms of time perception and self-recognition, while also investigating how the two processes might interact. We investigated how duration estimations when watching PLDs of human motion might be affected by performed speed of movement, agency (viewing “self” or “other”), movement type (more discrete or continuous), and whether time was estimated immediately after performing the action or after viewing the action. In this way, we aimed to provide novel insight into the hypothesised separate working memory processor for human movement (Wong et al., 2009) and theories of specific time perception mechanisms for biological motion (Gavazzi et al., 2013). We aimed to expand knowledge on action-perception coupling processes involving self-recognition mechanisms, by investigating how well people can recognise themselves in highly controlled dance-like movements and whether self-recognition ability is influenced by different performance speeds. Finally, we aimed to take a novel approach in drawing together self-recognition and time perception research, by exploring how these cognitive processes may interact through the derivation of timing information from inner motor representations. To this end, we investigated the effects of agency on duration estimations. In a more exploratory aim, we also investigated how agency and speed of movement affected appraisal of movements through ratings of expressivity and quality.

We hypothesise the following:

**Hypothesis 1:** Performed movement speed will influence duration estimation in accordance with previous findings that faster visual stimuli lead to longer duration estimations.

**Hypothesis 2:** Based on motor resonance theory, agency will influence duration estimation, such that duration estimations will be more accurate for self-stimuli.

**Hypothesis 3:** Estimating duration of an action immediately after performing it will differ from perceiving it later as a PLD.

**Hypothesis 4:** Performance speed will influence self-other discrimination accuracy, albeit the direction of the influence cannot be deduced from previous research.

## Methods

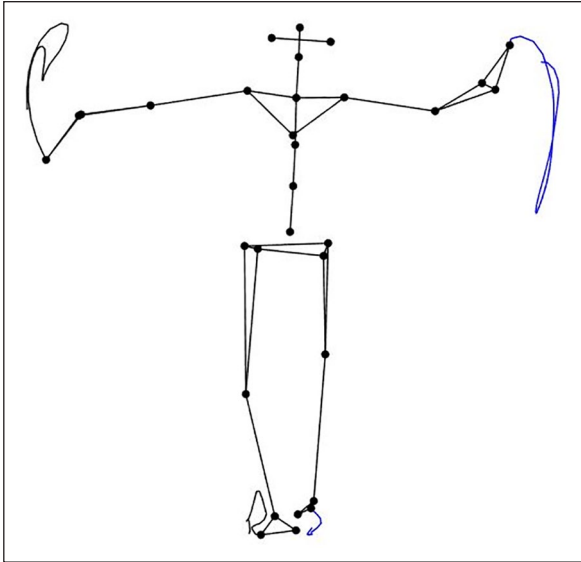
### Participants

In total, 37 participants (female = 23,  $M$  age = 27.39 years,  $SD$  = 7.4) of various nationalities and with varying levels of dance training were recruited via word of mouth and email lists to take part in individual motion capture recording sessions of several movement tasks (see below); 26 participants (female = 15,  $M$  age = 27.88 years,  $SD$  = 8.16, mean years of dance training = 4.31,  $SD$  = 4.71) then returned for the perceptual session, in which they watched back point-light animations of their own movements and that of another participant. While we aimed to have all 37 participants return for the second session, only 26 were able to return within a reasonable time frame. An a priori power analysis in G\*Power (Faul et al., 2007), with an estimated effect size of 0.25, an alpha of .05, and a power level of 0.8, yielded a minimum required sample size of  $N$  = 19, indicating that our obtained sample size was adequate. All participants had normal or corrected-to-normal vision, and were physically able to carry out the necessary movements. Some participants were awarded course credits for taking part, and others received €10 for each session. Participants took part in accordance with the Local Ethics Committee guidelines and gave written informed consent to take part.

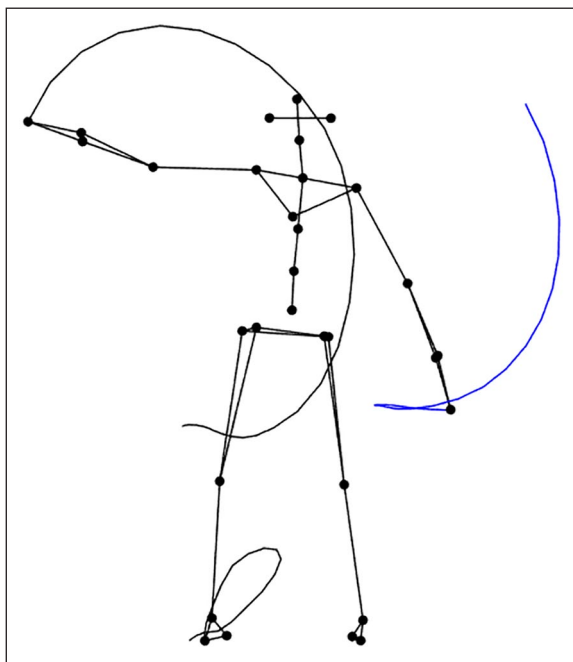
### Apparatus

Recordings were carried out in a quiet laboratory room, of approximately five by five metres. Eleven Qualisys Oqus cameras recorded motion capture data, and video footage was recorded using one Panasonic X920 video camera. Sound cues for indicating movement speed were played using AudioDesk software through a four-channel Neumann speaker system. Motion capture recordings were synchronised with the audio cues using SMPTE time code. Participants were outfitted with motion capture suits, and 31 reflective markers were placed on their bodies. The positions of the markers can be seen in Figures 1 and 2.

For the perceptual session, PLDs were created using the MoCap Toolbox (Burger & Toiviainen, 2013) in Matlab, animated at a frame rate of 25 frames per second and a viewing angle of 30 degrees from frontal view. PLDs were presented on a high-resolution LCD Dell monitor (23 inches, 100 Hz) using OpenSesame (Mathôt et al., 2012) experiment software, which was also used for randomisation of stimuli and response collection.



**Figure 1.** Single frame of right-left jumps showing motion trace for fingers and toes.



**Figure 2.** Single frame of knee circles movement showing motion trace for fingers and toes.

### Design and procedure

First, in a recording session, participants were taught and performed two types of repetitive dance-like movements while being recorded in optical motion capture. Dance-like movement was used because it provided a non-goal-based, non-habitual movement, which has rarely been used for self-recognition studies. To avoid confounding effects of familiarity with movement (Calvo-Merino et al., 2006),

we chose movements based on ipsilateral coordination between arms and legs. The movements were adapted from Tanaka Min's "Body Weather" dance training methodology (Marshall, 2006) and consisted of several repetitions (see Table 1).

Each participant was trained in performing the movements by an instructor with a professional dance background. Two types of movement were chosen that were either relatively slow and continuous ("knee circles") or fast and more discrete ("right-left jumps"). While none of the two movement types were strictly "discontinuous" (cf. Spencer et al., 2003), the main rationale was to choose two different movement patterns that may pose differences in terms of balance and motor control. Participants were recorded performing these two movements at three different speeds (slow, medium, and fast). Each of these six conditions were later presented as PLDs at three different lengths (short, medium, and long), creating 18 viewing conditions (see Table 1). The aim was to control as much as possible the duration (in seconds) of the stimuli across the different speeds, which meant that the number of repetitions varied across speed categories. Likewise, the number of repetitions between movement types varied to keep the duration of stimuli constant and to allow for comfortable movement execution. Each movement type and speed was both verbally described and physically demonstrated before being performed by the participants. There were between two and five recording attempts per participant, until adequate performance was achieved. These sessions lasted up to 2 hrs and one participant was excluded, as they were unable to perform the movements as required.

The speeds of the movements were indicated through sound stimuli created in Ableton Live. The medium speed was intended to provide a "comfortable" speed, while the slow and fast speeds were intended to challenge participants. The speeds were tested and adjusted in a pilot phase with five untrained and inexperienced participants. The start and end of the motion capture recordings were indicated with audible beeps.

For the right-left jumps movement, participants jumped from one leg to the other on the spot bringing one knee forward and up while bending the other knee and keeping the raised foot hanging, relaxed from the knee. At the same time, the arms were raised out to the side, parallel to the ground, and the wrists were flexed and extended in ipsilateral motion with the leg movement (see Figure 1). The speed was indicated by a metronome sound, and participants were directed to synchronise their foot touching the floor with the metronome.

For the knee circles movement, participants adopted a martial arts type posture with feet wide and turned out, and knees slightly bent. They then stepped from one leg to the other, moving their knees in circles while circling their ipsilateral arm (see Figure 2). Participants were instructed

**Table 1.** Number of repetitions, length in seconds (s), and tempo in BPM of PLDs.

Speed	Movement	Right–left jumps			Knee circles			
		Length	Short	Medium	Long	Short	Medium	Long
Fast	Repetitions		20	30	46	7	10	16
	Duration (s)		12.31	18.46	28.31	12.44	17.78	28.44
	Tempo (BPM)		195	195	195	67	67	67
Medium	Repetitions		13	20	30	4	7	10
	Duration (s)		12.00	18.46	27.70	10.67	18.67	26.76
	Tempo (BPM)		130	130	130	45	45	45
Slow	Repetitions		9	13	20	3	4.5	7
	Duration (s)		12.46	18.00	27.69	12.00	18.00	28.00
	Tempo (BPM)		86	86	86	30	30	30

BPM: beats per minute; PLDs: point-light displays.

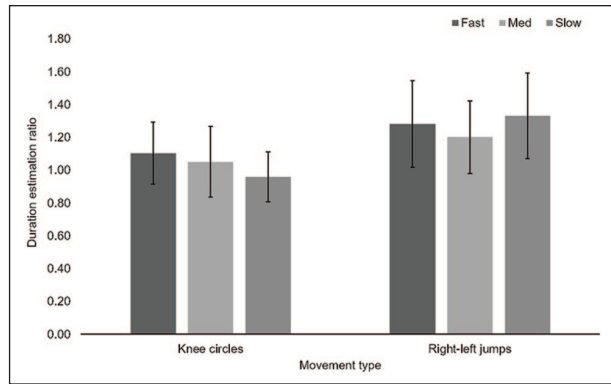
to keep their torso as still as possible. The speed was indicated by a sweep sound with oscillating pitch level (illustrating the circular characteristic of the movement), whereby the lowest pitch level indicated the moment the foot should meet the floor. As an additional everyday movement control, participants were recorded walking across the room. After each recording, participants were asked to estimate the duration of the action. The performed order of the movements was the same for all participants. This order was deemed necessary so that the learning process was logical and as easy as possible. Participants also filled out background questionnaires, including basic demographic information and number of years of dance training. These questionnaires were given in either English or German depending on the participant's native language.

In the perceptual session, which took place at least 1 month after the recording, participants viewed PLDs of themselves and one other person matched in terms of age, expertise, body type, and gender. In the first task of the perceptual session, participants were shown the PLDs of the two dance-like movements at the three movement speeds and durations (see Table 1), and were asked to estimate the duration of the animation in seconds (including decimals if they chose). These 36 stimuli (18 for self and 18 for other) were shown twice in a randomised order. In the second task of the perceptual session, participants were again shown the PLDs at the three movement speeds, this time using the short durations only, and including the walking PLDs, and were asked to indicate whether the person in the animation was them or someone else. They also rated quality (how “well done” the movement was) and expressiveness on 7-point rating scales. These 16 stimuli were shown twice in a randomised order, and responses were entered into the computer using the keyboard. After participants confirmed their response by pressing the enter key, the next stimulus was presented automatically with a delay of 4 s. This was programmed using OpenSesame software (Mathôt et al., 2012).

### Data analysis

All data were screened for outliers such that scores more than three standard deviations from the mean at any level of the dependent variable were excluded. This resulted in five participants being excluded from the duration estimation variable. One participant was excluded from the self–other responses as a problem with the experiment software caused the participant to only view each stimulus once instead of twice. This resulted in 21 participants for the duration estimation analysis and 25 for the self–other analysis.

From the self–other responses,  $d$ -prime and  $C$ -bias scores were calculated using R Studio version 1.2.5, according to signal detection theory (Macmillan & Creelman, 2005). The  $d$ -prime function from the Psycho package for R software (Makowski, 2018) was used, in which the hit rates and false alarms were adjusted according to Hautus (1995), to avoid the calculation of infinite values. Following signal detection theory, responses are labelled as correct self-identification (hits) and incorrect self-identification (false alarms), and from these data, a  $d$ -prime score and a  $C$  score are calculated for each stimulus and participant. The  $d$ -prime is a measure of the participant's sensitivity (i.e., ability to detect themselves from the presented stimuli), which takes both the correct and incorrect responses into account. A  $d$ -prime score above zero would indicate self-recognition better than chance, while scores below zero would indicate worse than chance. The  $C$  score is a measure of the participants' bias (i.e., tendency to think they see themselves regardless of whether they are correct). A  $C$  score above 0 would indicate tendency to respond “no,” while a  $C$  score below 0 would indicate a tendency to respond yes. Duration estimation data (processed in Matlab R2018b) were averaged across the two viewings and normalised by dividing the estimated time by the actual clock time of the observed stimulus, to provide the duration estimation ratio. The duration estimation ratio thus supplies information about how accurate the time estimation is, with a score of 1



**Figure 3.** Effect of speed within each movement, for the action condition. Error bars display 95% confidence intervals.

representing an exactly correct time estimation. In this way, time estimation across stimuli of differing durations can be compared (Vatakis et al., 2018). All further statistical analyses were carried out using IBM SPSS Statistics 24.0 software.

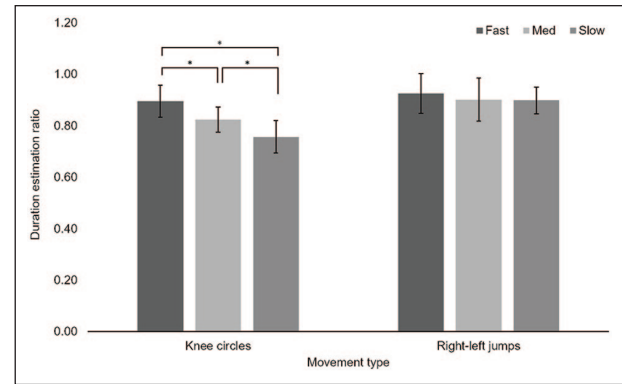
For duration estimations following the perception task, we ran an initial repeated-measures analysis of variance (ANOVA) with movement type, speed, agency, and length of stimuli as factors (Table 1). As results revealed no significant effect of length,  $F(1.29, 25.71)=1.40, p > .05$  (Greenhouse–Geisser correction), variables were averaged across the three different lengths, removing the length factor from the analysis.

## Results

Results are presented below for the dependent variables duration estimation (both following execution of the movements and watching the movements),  $d$ -prime scores (self-recognition), expressivity ratings, and quality ratings. We also present correlations of the above dependent variables with self-reported years of dance training, to explore possible associations with dance expertise. For all statistical tests, an alpha threshold of .05 was adopted.

### Duration estimation: action

For duration estimations, immediately following the movement tasks, a repeated-measures ANOVA was carried out with independent variables movement type (knee circles and right–left jumps) and speed (fast, medium, and slow), and dependent variable duration estimation ratio. Results showed a significant effect of movement type,  $F(1, 23)=8.72, p = .007, \eta_p^2 = .28$ , such that right–left jumps ( $M=1.27, SE=0.11$ ) was rated to be relatively longer than knee circles ( $M=1.04, SE=0.08$ ). There was no significant effect of speed,  $F(2, 46)=0.77, p > .05$ , and no significant interaction. Results are displayed in Figure 3.



**Figure 4.** Effects of speed within each movement type, for the perception condition. Error bars display 95% confidence interval; \* denotes significant difference at  $p < .05$ .

### Duration estimation: perception

A repeated-measures ANOVA was carried out with independent variables agency (self and other), movement type (knee circles and right–left jumps), and speed (fast, medium, and slow), and dependent variable duration estimation ratio. There was a significant effect of movement type,  $F(1, 20)=30.64, p < .001, \eta_p^2 = .60$ , such that right–left jumps ( $M=0.91, SE=0.03$ ) was rated significantly longer than knee circles ( $M=0.82, SE=0.03$ ). There was also a significant effect of speed,  $F(2, 40)=10.67, p < .001, \eta_p^2 = .35$ , and a significant interaction of movement and speed,  $F(2, 40)=4.62, p = .016, \eta_p^2 = .19$ . There was no effect of agency  $F(1, 20)=0.23, p > .05$ . For effect of speed, pairwise comparisons with Bonferroni corrections showed that fast ( $M=0.91, SE=0.03$ ) was rated significantly longer ( $p = .028$ ) than medium ( $M=0.86, SE=0.03$ ) and slow ( $p = .001, M=0.83, SE=0.02$ ), while medium and slow were not significantly different ( $p > .05$ ).

The interaction of speed and movement type was followed up with separate ANOVAs for each movement type with independent variables speed and agency (see Figure 4). Effect of speed was significant for knee circles,  $F(2, 40)=26.85, p < .001, \eta_p^2 = .57$ , but not for right–left jumps,  $F(2, 40)=0.45, p > .05$ . Pairwise comparisons with Bonferroni corrections revealed significant differences between fast and medium ( $p = .004$ ), fast and slow ( $p < .001$ ), and medium and slow ( $p = .004$ ), with fast rated the longest ( $M=0.89, SE=0.03$ ), followed by medium ( $M=0.82, SE=0.02$ ) and then slow ( $M=0.76, SE=0.03$ ). All mean duration estimations were less than one, meaning that for all speeds, stimuli were, on average, underrated.

For right–left jumps, there were no further significant effects or interactions, but for knee circles, there was a significant interaction of agency and speed,  $F(2, 40)=6.72, p = .003, \eta_p^2 = .25$ , suggesting that effects of speed on

**Table 2.** Descriptive statistics per condition for *d*-prime scores and *C* bias.

Movement	Speed	Mean <i>d</i> -prime	Standard error <i>d</i> -prime	Mean <i>C</i> bias	Standard error <i>C</i> bias
Knee circles	Fast	0.43*	0.21	0.22	0.09
	Medium	0.19	0.17	0.29	0.10
	Slow	0.27	0.13	0.37	0.08
Right-left jumps	Fast	0.20	0.19	0.33	0.10
	Medium	0.37	0.22	0.34	0.07
	Slow	0.35	0.19	0.21	0.09
Walking	–	0.27	0.20	0.52	0.07

\*denotes *p* value < .05 for one-sample *t*-tests comparing mean *d*-prime scores with 0.

duration estimation varied depending on whether the participant viewed themselves or someone else. Again, separate ANOVAs were carried out for the knee circles “self” stimuli, and knee circles “other” stimuli, with independent variable speed. For “self” stimuli, there was a significant effect of speed,  $F(2, 40)=6.60$ ,  $p=.003$ ,  $\eta_p^2=.25$ . Bonferroni-corrected pairwise comparisons showed that fast ( $M=0.85$ ,  $SE=0.03$ ) was rated significantly higher than slow ( $p=.003$ ,  $M=0.76$ ,  $SE=0.04$ ), but fast and slow were not significantly different to medium ( $p>.05$ ,  $M=0.82$ ,  $SE=0.03$ ). For “other” stimuli, there was also a significant effect of speed,  $F(2, 40)=30.89$ ,  $p<.001$ ,  $\eta_p^2=.61$ . Bonferroni-corrected pairwise comparisons showed significant differences between fast and medium ( $p<.001$ ), fast and slow ( $p<.001$ ), and medium and slow ( $p=.029$ ), again with fast rated highest ( $M=0.940$ ,  $SE=0.032$ ), slow rated lowest ( $M=0.751$ ,  $SE=0.029$ ), and medium in between ( $M=0.823$ ,  $SE=0.029$ ). Comparison of effect sizes suggests that the effect of speed on duration estimation was stronger when participants were watching others, and weaker when they were watching themselves.

### Duration estimation: comparing perception and action

To compare duration estimations between carrying out the action and watching the action, we conducted a repeated-measures ANOVA with factors mode (action and perception), movement type (knee circles and right-left jumps), and speed (fast, medium, and slow). There was a significant effect of mode,  $F(1, 22)=5.79$ ,  $p=.025$ ,  $\eta_p^2=.21$ , such that duration estimations immediately after action ( $M=1.15$ ,  $SE=0.09$ ) were longer than duration estimations immediately after perception ( $M=0.92$ ,  $SE=0.05$ ). There was also a significant effect of movement type,  $F(1, 22)=18.32$ ,  $p<.001$ ,  $\eta_p^2=.45$ , such that right-left jumps ( $M=1.13$ ,  $SE=0.08$ ) was rated longer than knee circles ( $M=0.93$ ,  $SE=0.05$ ). For effect of speed, the assumption of sphericity was violated and a Greenhouse-Geisser correction was used, showing no significant effect of speed,  $F(2, 44)=1.92$ ,  $p>.05$ . There were no interaction effects.

### Self-recognition

To investigate levels of self-recognition within each stimulus type, we conducted one-sample *t*-tests for each stimulus, comparing the mean *d*-prime score with 0. While self-recognition was generally above 0 (better than chance) for all conditions, the difference of the mean from 0 was statistically significant only in the knee circles fast stimuli,  $t(24)=2.08$ ,  $p=.049$ ,  $d=.41$ . For two other movement conditions, there was a non-significant tendency for self-recognition better than chance: knee circles slow,  $t(24)=2.04$ ,  $p=.052$ ,  $d=.40$ , and right-left jumps slow,  $t(24)=1.85$ ,  $p=.076$ ,  $d=.37$ . For all other conditions, self-recognition was not significantly better than chance, including walking. Mean *C*-bias scores were all above 0, indicating a tendency to respond “no” more often than “yes” in response to the question, “Is the person in the video you?” Results are displayed in Table 2.

To test for effects of agency, movement type, and speed on self-recognition ability, a repeated-measures ANOVA was conducted for the dance stimuli, with movement type (knee circles and right-left jumps) and movement speed (fast, medium, and slow) as independent variables, and *d*-prime scores as the dependent variable. There were no significant effects of movement type,  $F(1, 24)=0.001$ ,  $p>.05$ , or movement speed,  $F(2, 48)=0.04$ ,  $p>.05$ , and no significant interactions.

### Expressivity, quality, and expertise

To test for effects of agency, movement type, and speed on expressivity ratings, we conducted a repeated-measures ANOVA with independent variables agency (self-other), movement type (knee circles and right-left jumps), and speed (slow, medium, and fast), and dependent variable expressivity ratings (on a 7-point scale). While there was no effect of agency,  $F(1, 24)=0.02$ ,  $p>.05$ , or movement type,  $F(1, 24)=1.67$ ,  $p>.05$ , there was a significant effect of speed,  $F(2, 48)=6.22$ ,  $p=.004$ ,  $\eta_p^2=.21$ , and a significant interaction of movement type and speed,  $F(2, 48)=4.20$ ,  $p=.021$ ,  $\eta_p^2=.15$ . For the main effect of speed, pairwise comparisons with a Bonferroni correction showed



**Table 3.** Outcome variables correlated with expertise.

Variable	Spearman's correlations	$p$ value
$d$ -prime score	.19	.37
Duration estimation (action)	.29	.15
Duration estimation (perception)	.18	.40
Expressivity ratings	-.21	.31
Quality ratings	-.18	.38

significant differences between fast ( $M=3.46$ ,  $SE=0.15$ ) and medium ( $p=.042$ ,  $M=3.07$ ,  $SE=0.13$ ) as well as slow ( $p=.005$ ,  $M=3.09$ ,  $SE=0.10$ ), but medium and slow were not significantly different. To follow up the movement by speed interaction, separate ANOVAs were conducted for each movement type, revealing that the effect of speed was only present in the right-left jumps movement,  $F(2, 48)=13.02$ ,  $p<.001$ ,  $\eta_p^2=.35$ . Pairwise comparisons with Bonferroni corrections showed that fast ( $M=3.70$ ,  $SE=0.16$ ) was significantly higher ( $p<.001$ ) in expressivity than slow ( $M=2.93$ ,  $SE=0.16$ ), but not medium ( $p>.05$ ,  $M=3.30$ ,  $SE=0.15$ ), and slow was significantly lower in expressivity than medium ( $p=.034$ ).

Similarly, we conducted a repeated-measures ANOVA on quality ratings, with the same independent variables. For quality ratings, there were no main effects of agency,  $F(1, 24)=0.08$ ,  $p>.05$ , movement type,  $F(1, 24)=3.50$ ,  $p>.05$ , or speed,  $F(2, 48)=1.26$ ,  $p>.05$ , but there was a significant interaction between movement type and speed,  $F(2, 48)=3.99$ ,  $p=.025$ ,  $\eta_p^2=.14$ . Separate ANOVAs conducted for each movement type again revealed no effect of speed in knee circles,  $F(2, 48)=0.39$ ,  $p>.05$ , but a significant effect of speed in right-left jumps,  $F(2, 48)=6.09$ ,  $p=.004$ ,  $\eta_p^2=.20$ . Pairwise comparisons showed that the significant difference was between slow ( $M=3.41$ ,  $SE=0.14$ ) and medium ( $M=3.92$ ,  $SE=0.13$ ,  $p=.012$ ), while slow and medium were not significantly different to fast ( $p>.05$ ,  $M=3.75$ ,  $SE=0.14$ ).

To test for a potential association between our outcome variables and expertise, we ran Spearman's correlations between expertise (self-reported number of years of dance training) and outcome variables  $d$ -prime score, action duration estimation, perception duration estimation, expressivity, and quality ratings. Spearman's correlations were employed because the expertise variable was highly positively skewed, thus rendering parametric testing inappropriate. The alpha level was adjusted to  $\alpha=.01$  to allow for multiple comparisons. We found no significant correlations (see Table 3).

## Discussion

This study investigated duration estimation and self-recognition while watching PLDs of human biological motion. We aimed to test how duration estimation may be affected

by speed, agency (watching oneself or someone else), and type of movement. We also investigated how duration estimations differed between action and perception (carrying out a movement compared with watching it), and how self-recognition ability might be affected by speed and type of movement. We found that there was a significant effect of speed and movement type on duration estimations, such that faster speeds, and movements with higher number of repetitions, were estimated to be longer. The effect of speed was modulated by movement type, and also by agency, with a weaker effect of speed when participants watched themselves. Duration estimations immediately following action were significantly longer than estimations after perception. Furthermore, we found that self-recognition ability was not affected by speed or movement type, and that both expressivity and quality ratings were affected by speed.

### Duration estimation

We tested for effects of speed of movement, type of movement, and agency on duration estimations. It has previously been shown that speed of visual and audio stimuli affects duration estimation such that faster stimuli lead to longer duration estimations (e.g., Kaneko & Murakami, 2009; Zakay et al., 1983). This effect can be explained in accordance with change theory of time perception (Brown, 1995) or entrainment of the inner clock to the external stimulus tempo (Droit-Volet et al., 2013). However, this has not before been investigated in PLDs of real human motion. In fact, some evidence has suggested that speed effects on duration estimation may be restricted to non-biological motion such as computer-generated moving shapes or flashing lights (Gavazzi et al., 2013). Our hypothesis that speed would affect duration estimation was supported, showing a main effect of speed on duration estimations after watching the movements, with fast speeds rated significantly longer than medium and slow. Furthermore, we found that right-left jumps (the more discrete movement type) was rated significantly longer than knee circles. This finding is also in accordance with both the change theory of time perception and the internal clock model, as the more discrete movement had both a faster tempo (higher number of events in the same length of time) and higher rate of change. Our results are not in line with that of Gavazzi et al. (2013), as while they found no significant effect of speed on duration estimations for biological motion stimuli, we did find an effect of speed for human motion (a specific kind of biological motion). Their study was based on simulated, non-human movement, which may account for the different findings. Nonetheless, our results show that previously observed effects of speed of a visual stimulus on duration estimation also apply to stimuli consisting of human biological motion. Furthermore, in light of the hypothesised separate working

memory processor for human movement (Wong et al., 2009), our findings indicate that such a processor would also be susceptible to the biasing effects of speed on duration estimation of a visual human movement stimulus.

An interaction of speed and movement type revealed that significant effects of speed were present only in the more continuous movement type (knee circles). This interaction could be explained by the different numbers of repetitions in stimuli between the movement types. For example, the knee circles movement had a lower number of repetitions as the movement included more continuous motion. Therefore, number of repetitions may have been more salient in the right-left jumps movement, allowing participants to count the repetitions, which may have negated any effect of speed on time estimations. Indeed, previous literature has found that when temporal frequency is controlled for, faster speed of movement (i.e., velocity) actually results in shorter duration estimations (Sgouramani & Vatakis, 2014). In the current study, it was not possible to disentangle temporal frequency from velocity while maintaining similar durations across movement types and speeds, so our findings are limited in this sense. However, our results enable us to see how effects of speed on duration estimation differ between two movement types: one more continuous movement in which velocity of motion is arguably more salient, and the other more discrete movement in which temporal frequency is arguably more salient. Our results show that there was an effect of speed only for the more continuous movement (knee circles). (Figure 4). This finding may suggest that movement velocity contributed to distortions in perceived time, while frequency of movement apparently did not (cf. Orgs et al., 2011). Other possible explanations for the difference between movement types also exist. The movements differed in spatial displacement and in overall tempo, both of which could have affected the salience of tempo changes. Indeed, the cognitive processing of time has been shown to be affected by aspects of spatial processing (Grondin, 2010; Sgouramani & Vatakis, 2014; Tayama et al., 1987); thus, the bigger spatial displacement in knee circles may account for our effects.

As it has been theorised that motion knowledge from internal motor representations informs our perception of time (Gavazzi et al., 2013), we hypothesised an effect of agency on duration estimations after watching the movements, reflecting differing cognitive processes for watching oneself and another. While this hypothesis was not directly supported, as we found no main effect of agency on duration estimation, we did find an interaction effect of speed and agency within the knee circles movement such that effects of speed were stronger for “other” stimuli, compared with “self” stimuli. In addition, we found no effect of speed on duration estimations immediately following action, which may imply that the biasing effects of speed during the perception condition were specific to visual

modality processing. However, a similar effect of speed has been shown in tactile sensing (Tomassini et al., 2011), so it would have been reasonable to expect an effect of speed during action, processed through touch sensing of movements. We could posit that carrying out an action creates an inner motor representation containing temporal information which is unbiased by speed—possibly aided by spatial-temporal information gained from the action process (cf. Knoblich & Prinz, 2001). When watching back our own movement, this inner motor representation may dampen, but not eliminate, the biasing visual effects of speed. This would be in accordance with the direct-matching hypothesis (Rizzolatti et al., 2001) and Gavazzi et al.’s (2013) suggestion that the matching of perceived motion to inner motion representations informs our estimations of time. This possibility could be further studied utilising actions that have been previously shown to be reliably self-recognised, as higher rates of self-recognition may show different effects of agency on duration estimation.

We further found that duration estimations after action were significantly longer than duration estimations after perception. This could have been caused by increased arousal immediately following the actions, in line with findings that increases in reported and emotional arousal dilate experiences of time (Schwarz et al., 2012). However, it should be noted that heart rate has been shown to be unrelated to duration estimations (Schwarz et al., 2012), so physiological arousal alone would likely not account for this effect. Nonetheless, such differences in time perception between action and perception conditions may have implications for the development of virtual reality games, where a traditional video game involves merely perceiving, while a virtual reality game involves acting out movements. The purported change in time perception between the two conditions may have implications for how we perceive time in a virtual reality game and relate to the game’s environment.

### *Self-recognition*

Previous studies have shown that individuals can reliably identify themselves from motion information alone (Beardsworth & Buckner, 1981; Cutting & Kozlowski, 1977; Sevdalis & Keller, 2010). However, we found relatively low self-other discrimination ability in our sample compared with some previous studies (e.g., Loula et al., 2005; Sevdalis & Keller, 2010), with self-recognition reaching levels statistically better than chance in only one movement condition (fast knee circles). Research indicates that discrimination ability is better in more expressive movements (Loula et al., 2005), less constrained actions (Sevdalis & Keller, 2010), highly skilled actions (Hohmann et al., 2011; Wöllner, 2012), and more complex actions (Daprati et al., 2007). Our finding that self-recognition was, overall, not above chance for the highly

controlled, relatively inexpressive movements used in the current study further supports the notion that self-recognition may be more difficult for less expressive, more constrained actions.

Furthermore, our finding that self–other discrimination for walking was not statistically better than chance highlights inconsistent findings in the literature. While some evidence suggests that people can reliably recognise themselves from gait patterns (Beardsworth & Buckner, 1981; Sevdalis & Keller, 2010; Wolff, 1932), other evidence is more in line with our own findings that self-recognition from walking is no better than chance (Loula et al., 2005; Wöllner, 2012).

We investigated the effects of speed and movement type on self–other discrimination and found no significant effects. Thus, our results do not support a preferred tempo or movement type for motor resonance. Our findings are in accordance with that of Repp and Knoblich (2004), who found that pianists' self-recognition judgements were unaffected by altering the playback speeds of recordings. However, our approach of testing for effects of *performed* speed is, to our knowledge, novel.

We tested for effects of agency, movement type, and speed on ratings of perceived expressivity and quality. We found an effect of speed on quality and expressivity ratings, for the right–left jumps movement (more discrete) only, indicating that fast stimuli were rated to be most expressive, while medium speed stimuli were rated highest in quality. These results show that ratings of expressivity and quality are conceptually distinct, which is in line with previous research on music performances (e.g., Van Zijl & Luck, 2013). That right–left jumps were rated as more expressive when they were performed faster, could indicate that faster visual stimuli increased arousal, leading to higher levels of felt emotion. If we consider expressivity ratings indicative of participants' emotional experience, this would be in accordance with the arousal hypothesis of emotions (Rickard, 2004). In terms of quality ratings, it is logical that the medium speed movements would be judged as best, as this was most likely the easiest speed at which to perform the movements well.

There were no effects of agency on expressivity or quality ratings, indicating that participants' judgements did not depend on whether they were watching themselves or someone else perform. This finding is in contrast to Wöllner (2012), who found that expert conductors rated their own performances as better quality than others regardless of their ability to recognise themselves. This difference may be explained by the fact that participants in the current study were not experts in the dance movements performed, and thus were not practised in assessing quality and expression in these movements.

Finally, we found no correlations between dance expertise and any of our outcome variables. Our finding that expertise was not associated with self-recognition ability is in contrast to theories that expertise in a motor skill may

produce higher perceptual sensitivity to one's own actions (Repp & Knoblich, 2004); however, studies using more complex movements and clearly defined expertise groups may produce different results.

### Limitations

The perceptual effects discussed in this study could be limited to the specific movements and speeds used. Future research should aim to replicate these results in different movements and a different range of speeds. Furthermore, the sample used in this study was relatively small. Due to the novelty of the findings presented, replication with a larger sample would strengthen the theoretical implications discussed. In addition, the ability to test for effects of expertise in this study was limited as the expertise variable was not evenly distributed.

Another limitation of the current study is the way in which the point-light animation is displayed. Most previous studies on self–other discrimination from PLDs have used a relatively simple marker set of up to 18 markers. In the current study, we used a model of 32 markers, including visualisation of bones connecting the markers (see Figures 1 and 2). Our aim was to include a wider range of motion information, but the complexity of our animations may have led to an overload of information and an unrealistic view of the figure. Sevdalis and Keller (2010) showed that self-recognition from clapping was still reliable with as little as two markers, but to our knowledge, no study has looked at how *increasing* the complexity of animations might affect self-recognition. We suggest that further research is needed to explore how such differences in stimulus presentation may affect self–other discrimination from gait patterns.

Finally, in the stimuli creation for the current study, we chose to control duration of stimuli across the different movement speeds, which meant that the number of repetitions varied. Future research may aim to replicate the current findings in a stimulus set that controls temporal frequency.

### Conclusion

This study investigated effects of speed on duration estimation and agency identification from human motion observed in PLDs of dance-like movement. We further investigated how duration estimations differed between performing and watching movements, and effects on expressivity and quality ratings. Our results show that faster movement leads to longer duration estimations when watching human biological motion, in accordance with previous research in non-human movement (e.g., Droit-Volet et al., 2013; Tomassini et al., 2011) and in contrast to Gavazzi et al. (2013) who suggested such an illusion did not apply to biological motion. To our knowledge, this

study is novel in showing such an effect in real human motion. We further found that effects of speed were weaker for watching own movements compared with others' movements, which could be interpreted in accordance with the hypothesis that prior knowledge of motion calibrates our time perception (Gavazzi et al., 2013). We also found that duration estimation was longer immediately following action of movements compared with perception of movements, and that effects of speed did not apply immediately following movement action. These findings provide novel insight into timing mechanisms from watching human motion. Future research should extend the current findings to more expressive movements, which might provide different effects of agency on duration estimation, and directly compare duration estimation in human and non-human motion with respect to the hypothesised separate working memory for human motion (Wong et al., 2009).

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