

Part XII

Free Talk Session 7

USING THE EFFECTS OF FOREPERIOD-VARIATION ON READINESS TO BREAK IN DRIVING SIMULATION

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Abstract

Range and frequency of varying foreperiods in reaction time experiments affect the expectancy of the reaction signals and the readiness to react in a systematic manner. In a study investigating braking safety as a function of the driver's footwear we made use of this regularity. In order to provoke unforeseeable situations which require speedy brake applications at first the time intervals between consecutive braking signals (interstimulus interval; ISI) were varied so as to establish a time-reference-system. At later stages of the experiment, a few ISI at considerably lower durations were presented. These ISI perceived as too short significantly increased breaking times if the subjects wore flip-flops compared to foot-covering shoes.

Reaction times are influenced by the foreperiod (FP) which is the interval between a warning signal applied to direct attention to an upcoming reaction signal and the stimulus. If the FP is kept constant within a range of 1 to 7 s in single reaction experiments, we find reaction times (RTs) nearly linearly decreasing with increasing length of FP (Fig. 1). When we present variable FP, however, reaction time follows a typical pattern as shown in Fig. 2 with relatively slow reactions at the shortest FP and decreasing RT up to the median FP. For longer than medium FPs the RT remains constant (Müller, 1980). These data are in line with results shown by Baumeister et al. (1967) and Niemi (1979).

For Fig. 2 the RTs are averaged over the relative length of FPs out of 4 series each consisting of equally spaced FPs ranging from either 1 to 4 s; 2.5 to 5.5 s, 4 to 7 s or 1 to 7 s. The effect of FP on RT is less pronounced if FPs are presented in random order compared to a condition where the same sequence of FPs is repeatedly presented.

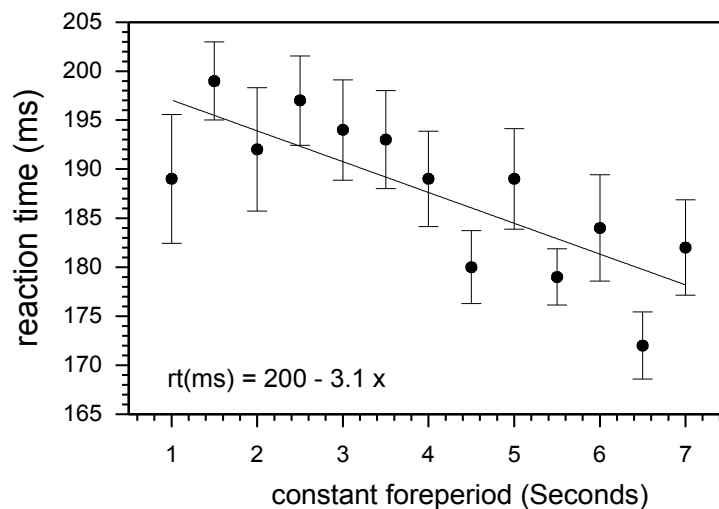


Fig. 1. RT to signals of white light at constant foreperiods between 1 and 7 s.

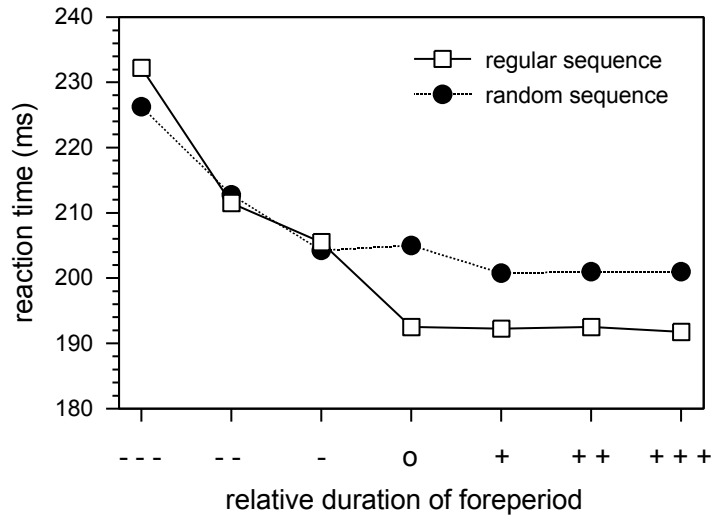


Fig. 2. RT to signals of white light at relative positions of the foreperiods in time-reference-systems.

In a paper given at Fechner Day 92 (Müller, 1992) it was shown that the RT is linearly related to category-scaled psychological tension. It was argued that in each case the set of FPs forms an orienting time reference system (*Zeitbezugssystem*) according to Witte (1966) and Heller (1990) wherein subjects try to maximize readiness for the midpoint between shortest and longest FP of the system. If the reaction signal appears at this point readiness will be optimized, resulting in short RT. If the signal appears later, a reactive increase of psychological tension is mobilized (Düker, 1963) which prevents a slowing of RT for longer than medium FP (Müller, 1981).

Prompting critical reactions using a foreperiod-reference system

If the above outlined thoughts hold, we expect participants being astonished and unprepared if unexpectedly a FP appears which is clearly shorter than the shortest in an established time reference system. In experiments designed to evaluate the effect of different footwear on the brake application time (Backhaus & Müller, 2016) in a driving simulator (following an cross-modal ABBA-design), 40 participants each executed 84 braking actions when using enclosing footwear and when wearing flip-flops. In order to provoke critical braking manoeuvres at first 5 different ISI of either 10, 12.5, 15, 17.5 and 20 s between upcoming braking signals (yellow light, red light or a person suddenly appearing on the street) were presented three times in succession in irregular order. Then the 16th signal appeared unexpected already after 4 s. During the time course of the entire experiment this pattern (15 time system conforming ISI followed by an unusual short period) was repeated 8 times; interrupted by two breaks which were used to change footwear. The driving task required to follow an imagined, hence not visible pathway directed by two laterally displayed arrows which indicated the direction of deviations from the track. This task alone absorbs a high degree of attention, which overall causes relatively long reaction times.

Despite the fact that attention of the participants was focussed on the tracking task and various aspects of the experimental setup, as the change of stimuli and footwear interrupted and altered the flow of the experiments, the overall recorded RTs (960 tri-

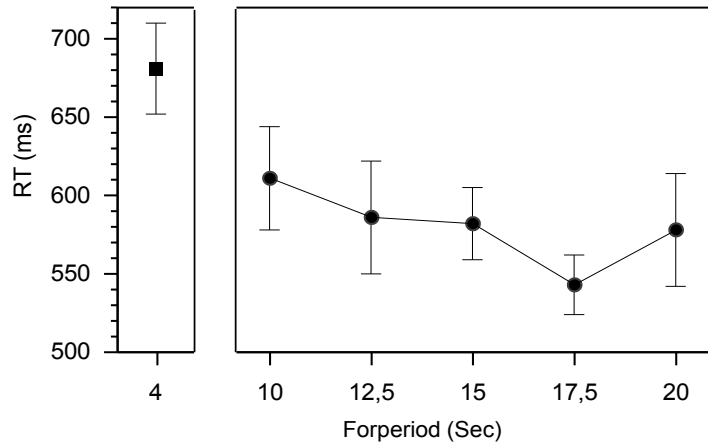


Fig. 3. On the right: Breaking response to traffic lights and persons on the road at variable ISI. Left: Reaction to rare ISI outside the time reference system.

als/foreperiod) given with Fig. 3 show a foreperiod-dependency near to the one described in Fig. 2. The intention to provoke a critical break-condition by introducing a FP outside the time reference system was achieved as shown in the very left mark in Fig. 3. For this critical ISI it was clearly demonstrated that breaking time, defined as the interval between signal-onset and full application of the brake pedal, is longer if subjects wear flip-flops (mean = 1110 ms; SD = 287) compared to foot-covering shoes (mean = 1017, SD = 177); ($t = 2.665, p < 0.01$).

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ACCURACY AND LATENCY OF KICKING FOOT IDENTIFICATION FOR FOOTBALL OPPONENTS IN RELATION TO TEAM FAMILIARITY AND GAME EXPERIENCE

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Abstract

Although only 18% of Australian Football players are left-footed, defending against them requires different strategies to defending against right-footers. This research collected both discrimination and response latency data to examine the ability of football players to identify left- versus right-footed kickers. Players identified the kicking foot of teammates and opponents from static facial images presented in a randomised sequence. Accuracy, reaction time (RT), and discrimination capability (AUC) were examined. Participants were less accurate and had slower RTs when identifying the kicking foot of opposing team players compared to that of their teammates. Left-footed opponents who had played for longer were identified with greater accuracy and reduced RT, and participant game experience correlated with faster RT. Opposing team familiarity and game experience were both found to affect kicking foot identification in Australian Football and this finding has potential for training and performance benefits.

Research in perceptual-cognitive sport expertise has consistently demonstrated superior acquired characteristics in highly experienced or expert performers relative to intermediates or novices (Abernethy et al., 2012). In both team and individual sport contexts, it is visual and perceptual domain exposure along with the development of sport-specific knowledge and memory (Roca et al., 2013) accumulated via extensive training and competition that appear critical to perceptual-cognitive skill.

The ability to identify and respond to laterally associated movement is evident in many sporting contexts (Raymond et al., 1996). In AF, perceptual-cognitive skills are particularly important (Farrow et al., 2008) as players continuously interact with opponents and teammates at different distances when executing a kick, evading a tackle (Bradshaw et al., 2011) or when receiving or defending a pass (Steel et al., 2011). Although both sides can be used for kicking and handballing in AF (Parrington et al., 2015), most elite players exhibit a strong ‘footedness’ preference (Ball, 2011) and coaches expect the dominant foot to be used in most instances (Farrow & Ball, 2011). The frequency of left-footed players in AF is estimated to be approximately 20% (Champion Data, 2015).

In the absence of knowledge regarding kicking-foot preference, the reliance on using ‘present time’ player biological motion to make decisions may lead to missed opportunities (Ward & Williams, 2003). These concerns are likely more pertinent in less experienced players, who are less able to extract meaning from kinematics for forthcoming movements (Steel et al., 2006). Therefore, a player’s default option—based on lower frequencies and experience—may be to assume that an opposing player has a right-foot kicking preference; even though this may be costly (Loffing et al., 2015). To illustrate, Figure 1 highlights



Fig. 1. Illustration of Kicking-Foot identification error in professional AF (a) The defender preparing to ‘man-the-mark’ goes towards the right shoulder of the opposing player. He is expecting the opponent to swivel right and use his right foot for kicking (b) The attacking player receives the ball and steps to his left. The defender is still moving towards the right shoulder of the attacker (c) The attacking player now prepares to kick using his left foot. The defender is out of position and cannot react quickly enough to tackle and prevent a ‘left-foot’ kick (d) The attacking player makes a successful forward kick using his left foot.

the occurrence and consequence of such an error in a professional AF game. The offensive player has time and space to kick with the preferred left-foot after the defender incorrectly assumes or inaccurately identifies a right-footed kick. Such perceptual-cognitive error can lead to points conceded, hence determining whether players are less accurate or slower in recognising the less frequent left-footed players is significant (Abernethy et al., 2001).

The aim of this study was to determine whether professional AF players’ accuracy, reaction time, and discrimination of ‘Kicking Foot’ identification (Kicking Foot-ID) were affected by left- v right-footer frequencies, team-mates v opposing team members, and game experience. Hypothesis 1 stated participants would be less accurate, and slower in identifying left-footers. Hypothesis 2 predicted participants would be more accurate, faster, and more capable in identifying the preferred kicking-foot of teammates than opposing players. Hypothesis 3 predicted that game experience would moderate these capabilities, leading to better accuracy, lower RT’s, and an enhanced capability to discriminate the preferred kicking foot used by opposing players. Likewise, opposing players with more game experience would be more accurately and quickly identified.

Method

The study was undertaken on two separate occasions during the final third of an AFL season. Different participant groups were used on each occasion, and participation in either Part 1 or 2 of the study was aligned to those players selected to play against the upcoming opposing team in that week of the season (i.e. Opponent 1 or Opponent 2)



Fig. 2. Diagrammatic illustration of randomised sequence presentation for the first 7 photographs for Opponent 1 test with Own Team players inter-dispersed (note: each player’s head and shoulders were included in the actual presentation).

Participants

13 and 10 male AF players respectively, from a professional football club, participated in parts 1 and/or 2 of the study (3 participated in both parts). Participants had varying levels of ‘first-grade’ AF competition experience (Opponent 1 participant group— M games played = 122.6, $SD \pm 80.4$; Opponent 2 participant group— $M = 117.4$, $SD \pm 82.6$).

Procedure

Participants completed a standardised 15-minute Kicking Foot-ID video task using a 38cm notebook monitor (ACER Aspire 9420). Participants were shown a randomised sequence of 60 player photos that included 30 teammates and 30 upcoming opposing team players. Opponent players were chosen for the sequence based on those players most frequently selected in the team’s playing squad up to that point in the season. Figure 2 provides an illustration of the player video presentation. Participants had to identify as accurately and quickly as possible, the kicking-foot preference (i.e. left or right-footed) of each player. Kicking-foot preference was determined using the player profiles held by Champion Data Statistics (Champion Data, 2015). Seven of thirty “Own Team” players (i.e. 23%), nine of thirty in Opposition Team 1 (30%) and six of thirty in Opposition Team 2 (20%) were left-footed.

A latency-timing box (Steel et al., 2006) captured participant responses. The box panel consisted of a central home key (starting position) and six equidistant (i.e. 5.18 cm) response certainty keys, arranged adjacent and in a semi-circular pattern. Participants applied dominant hand index finger pressure on the home key and responded by moving to a choice key as quickly as possible. The three key choices to the right represented levels of certainty for a right-foot identification decision (i.e., RF-LC = Right Foot–Low Certainty; RF-MC = Right Foot–Medium Certainty; RF-HC = Right Foot–High Certainty), while the three keys to the left represented certainty levels for a left-foot decision (LF-LC = Left Foot–Low Certainty; LF-MC = Left Foot–Medium Certainty; LF-HC—Left Foot–High Certainty). The latency-timing device enabled valid measurement of Response Accuracy, Reaction Time (i.e., initial release of pressure from home key), and Response Certainty. Participants completed the Kicking Foot-ID task in an afternoon two days prior to an upcoming game.

Data Analysis

Accuracy & Latency (Reaction Time). Kicking Foot-ID accuracy (% correct) and latency (RT ms) were analysed separately using a two-factor Repeated Measures (RM) ANOVA, with the factors of Foot (Left-Right) and Team (Own-Opposition) entered as independent variables.

Foot Preference Discrimination: Receiver Operating Curve (ROC) analysis. To assess participant capability in Kicking Foot-ID, a non-parametric signal detection Receiver Operating Curve (ROC) analysis was used (Swets et al., 2000). Left-footers were considered as signals and right-footers as noise, and decision certainty levels represented different response cut-offs. Data were entered into the ROC sub-routine within SPSS (Version 22.0 SPSS, Inc., Chicago, IL). Preferred foot (i.e., 'left or right-footer') was entered as a state variable and certainty rating entered as the continuous variable. The ROC routine generated an area under the curve (AUC) value for each participant reflecting accuracy and certainty, with 0.5 representing chance and 1.0 representing perfect Kicking Foot-ID discrimination. A paired t-test examined the difference between Own-Team and Opposition-Team members.

Game Experience. To determine whether player game experiences affected preferred Kicking Foot-ID, Pearson's correlations examined whether participants' own professional game experience (i.e., AF games played), and the number of games played by an opponent were correlated with Kicking Foot-ID accuracy, RT, and discrimination capability.

Results

Accuracy of Kicking Foot Identification (KF-ID)

Opponent 1. RM-ANOVA revealed significant main effects for Foot, $F_{(1,12)} = 101.53$, $p < 0.001$, $\eta_p^2 = 0.89$ and Team, $F_{(1,12)} = 115.48$, $p < 0.001$, $\eta_p^2 = 0.91$. Identification accuracy was lower when participants attempted to identify left-footed players, and when they attempted to identify the kicking foot of opposition players. Likewise, there was a Foot x Team interaction, $F_{(1,12)} = 103.33$, $p < 0.001$, $\eta_p^2 = 0.90$. The reduction in identification accuracy when viewing left-footers relative to right-footers was greater for participants when they viewed opposing team members compared to when viewing teammates.

Opponent 2. RM-ANOVA revealed that while mean patterns were close to significance, no main effect for Foot was evident, $F_{(1,9)} = 3.94$, $p = 0.08$, $\eta_p^2 = 0.30$, or the interaction, $F_{(1,9)} = 4.432$, $p = 0.07$, $\eta_p^2 = 0.33$. However, a main effect for Team was evident, $F_{(1,9)} = 7.97$, $p < 0.05$, $\eta_p^2 = 0.47$. Identification accuracy was lower when participants attempted to identify the kicking foot of opposition players.

Latency of KF-ID (Reaction Time)

Opponent 1. RM-ANOVA identified no main effect for Foot, $F_{(1,12)} = 1.56$, $p = 0.24$, $\eta_p^2 = 0.12$, though a significant main effect for Team was apparent, $F_{(1,12)} = 25.51$, $p < 0.001$, $\eta_p^2 = 0.68$, with slower reaction times occurring when participants were responding to images of opposing players. There was no interaction, $F_{(1,12)} = 0.01$, $p = 0.91$, $\eta_p^2 =$

0.001.

Opponent 2. There was again no main effect for Foot, $F_{(1,9)} = 0.09, p = 0.77, \eta_p^2 = 0.01$, though there was a main effect for Team, $F_{(1,9)} = 65.39, p < 0.001, \eta_p^2 = 0.88$, with slower reaction times when recognising opposing players. The interaction was significant, $F_{(1,9)} = 5.62, p < 0.05, \eta_p^2 = 0.39$, as participants were faster in reacting to left-footers in Opposition 2 team members. This suggested something unique about Opposition 2, and a follow-up t -test revealed that career games played by Opposition 2 members ($M = 116.55, SD = 83.15$) was significantly greater than Opposition 1 ($M = 75.07, SD = 66.35; t(60) = -1.98, p < 0.05$). The game differences specifically in left-footers was not significant, though the small sample size and descriptive statistics should be noted (i.e., Opponent 2— $M = 135.5$ games; $SD = 63.49$; Opponent 1— $M = 77.44$ games; $SD = 78.52$).

Foot Preference Discrimination: ROC Analysis

Opponent 1. ROC analysis produced AUC scores indicating the capability to identify left-footers from right-footers in the sample of players. A paired t -test between Own-Team (AUC $M = 1.0$) and Opponent 1 (AUC $M = 0.81$) showed a significant superiority in the capability to identify left-footers amongst teammates relative to opposing team members ($p < 0.001$, M difference in AUC = 0.19, 95% CI = 0.12–0.25).

Opponent 2. Similarly, the t -test for Own-Team (AUC $M = 0.99$) and Opponent 2 (AUC $M = 0.88$) also showed a superior capability in identifying left-footers amongst teammates relative to Opposing team members ($p < 0.05$, M difference in AUC = 0.11, 95% CI = 0.03–0.19).

Game Experience

Opponent 1 The number of games played by participants was not correlated with Kicking Foot-ID accuracy or associated with discrimination capability (i.e., AUC scores, $r = 0.29, p = 0.33$). However, games played was correlated with the average RT (i.e., left footers $r = -0.59, p < 0.05$; right-footers, $r = -0.62, p < 0.05$); that is, participant game experience was associated with faster RT's. When opposition members had more game experience, accuracy increased when participants attempted to identify left-footers ($r = 0.71, p < 0.05$) but not right-footers ($r = 0.27, p = 0.12$), and average RT's reduced (i.e., left-footers, $r = -0.72, p < 0.05$; right-footers, $r = -0.63, p < 0.005$).

Opponent 2. The number of career games played by participants was not correlated with Kicking Foot-ID accuracy, average RT or discrimination capability. Professional game experience in Opponent 2 members was not correlated with Kicking-Foot ID accuracy. However, it was associated with reductions in average RT for Kicking Foot-ID for right-footers ($r = -0.84, p < 0.005$), but not left-footers.

Discussion

For Opponent 1, professional AF participants were significantly less accurate in identifying left-footed than right-footed players, and the accuracy of identifying the preferred foot was

greater when viewing team-mates compared to when viewing opposing team members. By contrast, laterality did not affect RT's. These findings provide partial support for Hypothesis 1, the frequency-dependent hypothesis (Raymond et al., 1996), suggesting that lower frequency encounters with left-handers/footers could confirm identification accuracy performance advantages in selective sporting situations (Hagemann, 2009).

For Opponent 2, laterality did not affect accuracy and did not affect RT's. However, the RT interaction was significant. When participants attempted to discern the preferred foot of opponent left-footers, RT's were quicker than when viewing opposition right-footers; a finding which might be explained by Opposition 2 containing players with a significantly greater number of AF games played (i.e., reflecting higher familiarity). Correlations support this notion, as opponent team member game experience was associated with improved recognition accuracy and quicker identification.

With reference to Hypothesis 2, findings across both upcoming opponents showed participants were more accurate and had faster RT's when viewing teammates. Participants were able to identify left-footers amongst teammates with more accuracy and certainty than left-footers for Opponent 1 and Opponent 2. So, whilst findings highlighted expected discrepancies in comparing Kicking Foot-ID capability when viewing own and opposing team members, they also highlight the potential benefit that could be achieved by using a similar protocol to train less experienced players to improve their perceptual capability (in terms of quickly and accurately identifying footedness) when competing against less familiar opponents (Schorer et al., 2012).

Results also provided partial support for Hypothesis 3. For Opponent 1 (i.e., the team with less-experienced and less-familiar players), participant game experience did not influence Kicking Foot-ID error, though experience was associated with faster RT's. However, more AF games played by opposing team members was associated with greater accuracy for identifying left-footed players and faster RT's in identifying both left- and right-footers. This is consistent with the view that accuracy and RT improvement can be accrued from opponent player familiarity and knowledge (Loffing et al., 2012a).

Conclusion

In two samples of professional AF players tasked with identifying the Kicking Foot of teammates and players from two opposing teams, participants made more errors and were slower when identifying the preferred kicking foot of opposing players who were (a) left-footed, (b) members of an opposing team, or (c) less familiar in general. These tendencies were moderated when opponent players were more familiar (e.g., Opposition 2) and had played a greater number of AF professional games. Perceptual training aimed at reducing Kicking Foot identification error and RT may be beneficial in improving the decision-making capability of AF players.

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CHARACTERISTICS OF SIMULTANEOUS TAPPING BY DIFFERENT HANDS/FEET

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Abstract

People require temporally precise coordination of multiple body parts to perform various motor tasks, e.g., playing a musical instrument. However, little is known about the mechanism by which the human brain produces and maintains precisely synchronized voluntary movement in multiple body parts. In the present study, we aimed to answer these questions by analyzing the temporal characteristics of bimanual simultaneous tapping. We also investigated how sensory feedback contributes to the maintenance of simultaneity by examining the inter-participant correlation of auditory or tactile temporal-order sensitivity and tapping simultaneity. We further explored how subjective simultaneity was determined using a hand-foot simultaneous tapping task. Our results suggest that humans can achieve temporally precise movement of two body parts more easily than we can discriminate these movements based on auditory or tactile information, though the movements may nevertheless be produced so that the two sensory feedback signals become simultaneous.

We often need to make simultaneous movements of multiple body parts to perform various motor tasks in daily life, including playing the piano and the drums. There have been studies on the mechanism by which we synchronize our action to an external rhythmic events (Repp, 2005; Repp & Su, 2013; Roy, Dalla Bella, & Lagarde, 2017) and on the mechanism by which we detect inter-sensory synchronization (Chen & Vroomen, 2013; Stein, 2012). However, little is known about the mechanisms involved in simultaneous voluntary movement of different body parts.

There are several possible events in the neural processing pathway that the brain tries to synchronize when moving different body parts. When we produce an action (e.g., tapping of a finger), a motor command is produced in our brain and transmitted to a motor organ to bring out a tapping action. Then, the action causes physical consequences, which are detected by sensory organs and transmitted to the brain as sensory feedbacks (e.g., tactile sensation from tapping, impulsive sound, and visual feedback). It is not clear which of these sensori-motor events is/are used to perform and maintain simultaneous tapping.

An important example of simultaneous movement in different body parts is bimanual tapping, which is necessary for activities such as playing musical instruments. However, in bimanual tapping, the sensory and motor pathways have almost the same transduction delay for both hands, and the relevant timing for performing simultaneous tapping cannot be dissociated completely. Therefore, we also used the hand-foot tapping task to overcome this limitation. If the brain produces simultaneous motor commands, movements in the hand should precede those in the foot due to the transduction delay in motor commands. In contrast, if the brain attempts to simultaneously receive tactile feedback signals, sensory signals from the foot should precede those from the hand because tactile sensory signals need more time to reach the brain. Another possibility is that the brain compensates for the delay in motor and sensory signals (Harrar & Harris, 2005) to achieve actual simultaneous tapping. By investigating hand-foot tapping, we can identify

these possibilities and gain an insight into the mechanism involved in simultaneous body movement.

In this paper, we investigated the mechanism of simultaneous movement in different body parts by examining bimanual and hand-foot simultaneous tapping in detail. First, we measured the temporal interval of bimanual tapping, and investigated how it could be related to the temporal discriminability of sensory perception, assessed as the temporal threshold of tactile and auditory temporal-order judgment. Next, using the hand-foot tapping task, we aimed to dissociate the timing used to achieve simultaneous tapping of the hand and foot.

Method

Seventeen (15 male and 2 female) people participated in the bimanual tapping task and the perceptual temporal-order judgment (TOJ) task. One male participant was excluded from the following analyses because the participant was unable to perform the tactile TOJ task. Six out of the remaining 16 participants also participated in the hand-foot tapping task. These experiments were approved by the ethics committee at the University of Electro-communications.

Bimanual and Hand-Foot Tapping Tasks

In the bimanual tapping task, participants sat on a chair and naturally placed their hands on tables located on both sides of the chair. Tapping was monitored using contact microphones (AKG, C411PP), which were placed on the surface of the tables near the participants' fingers, and the signals from the microphones were recorded using an audio-interface device (Roland, OCTA-CAPTURE) at a 96-kHz sampling rate. Participants were instructed to close their eyes and tap the tables using their right and left index fingers as simultaneously as possible. They were instructed to continue the tapping task at their own pace, without making a periodic rhythm. The experiment was divided into 3 sessions with a short break between the sessions. Each session was approximately 3 min long.

In the hand-foot tapping task, participants placed one foot (e.g., left foot) on a board located on the floor and tapped the thumb finger of the foot simultaneously with the index finger of the hand on the other side (e.g., right hand). The side of the hand/foot to be used was counterbalanced across participants. Other experimental details were the same as in the bimanual tapping task.

Perceptual Temporal-Order Judgement Tasks

In the perceptual TOJ tasks, participants sat on a chair and a pair of either tactile or auditory stimuli were presented to them. The participants judged which of the two stimuli, right or left, was presented first. In the tactile TOJ task, the participants placed both hands at nearly the same position as those in the bimanual tapping task, and short (~ 1 ms) tactile stimuli were delivered to their index fingers using vibrating devices. Stimulus onset asynchrony (SOA) between right and left stimuli was randomly chosen for each trial from -100 ms to 100 ms (plus sign indicates right stimulus first) with 10-ms intervals. Each SOA was repeated 10 times, for a total of 210 trials. In the tactile condition, white noise was always presented via headphones to block sounds from the vibrator. In the auditory

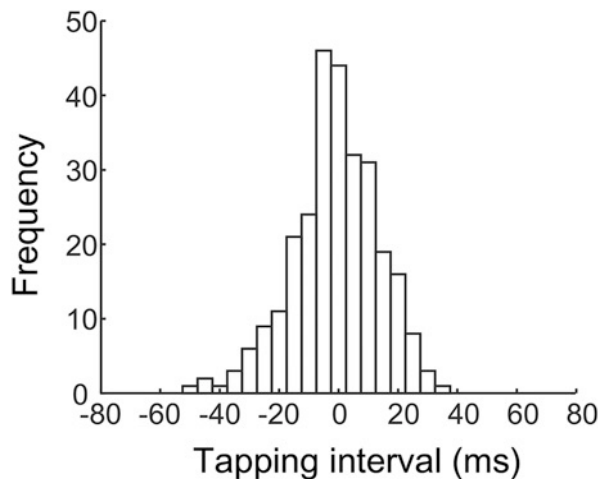


Fig. 1. Histogram of tapping interval for a representative participant. Plus sign indicates that the right hand was tapped before the left hand.

TOJ task, a pair of short “click” sounds were presented via two loud speakers (Bose, MM-1) placed near the participants’ hand in the bimanual task. The SOA between the right and left stimuli were also randomly chosen from -100 ms to 100 ms with 10-ms intervals, but without 0 ms SOA in the auditory condition. Each SOA was repeated 10 times, for a total of 200 trials.

In both tasks, participants were instructed to close their eyes and their task was to identify the stimulus that was presented first by pressing either the left or right foot switch placed on the floor.

The results of the TOJ tasks were fitted to a cumulative Gaussian psychometric function, and the point of subjective simultaneity (PSS) and the just noticeable difference (JND), defined as the temporal difference between PSS and either 75% or 25% judgment rate point, were calculated for each participant and task condition.

Results

Most participants performed temporally precise bimanual tapping, distributed around an almost 0 ms temporal interval (Fig. 1 for a representative participant.) The precision, i.e., the standard deviation, of tapping was about 10 ms and surprisingly uniform across participants (Fig. 2.) The JNDs for the tactile and auditory TOJ tasks were roughly in the 30–40 ms range (Fig. 2) and much worse than the tapping precision (paired t -test, $p < 10^{-4}$), suggesting that both tactile and auditory sensory feedbacks are not temporally sensitive enough to reliably compensate for the temporal delay between tapping. As additional evidence that the sensory feedback is not directly relevant to tapping precision, we checked the across-participant correlation between tapping precision and sensory JNDs (Fig. 3). The results clearly show that there was no correlation between tapping precision and temporal sensitivity in sensory perception ($p = 0.86$ for tactile and $p = 0.49$ for auditory result as an output of MATLAB’s `corrcoef` function).

Next, we analyzed hand-foot tapping to investigate whether sensory feedback contributes to the adjustment of the accuracy of simultaneous multiple tapping in different body parts. The results show that the foot was tapped first (Fig. 4, t -test, $p = 0.048$) in

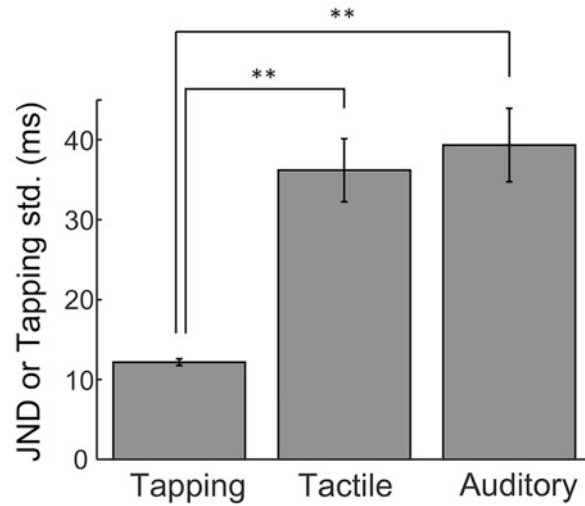


Fig. 2. Comparison between the standard deviation of bimanual tapping and the just noticeable difference (JND) of the tactile or auditory TOJ task. The error bars show their standard error across participants (** $p < 10^{-4}$).

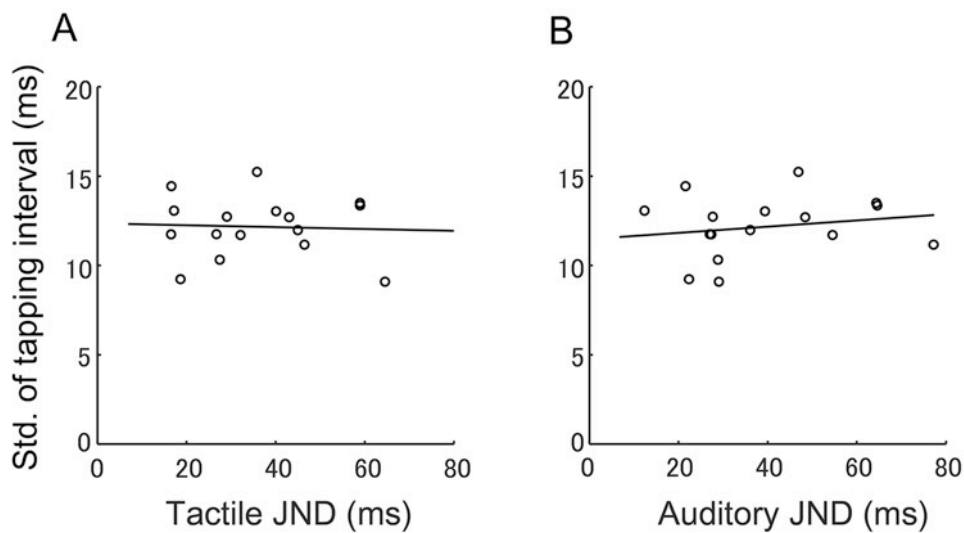


Fig. 3. Scatter plots for just noticeable difference (JND) in A) tactile and B) auditory tasks vs. standard deviation of the tapping interval in the bimanual task. The solid lines indicate linear regression.

the hand-foot tapping task, even though tapping was simultaneous on average in the bimanual tapping task (t -test, $p = 0.58$), and the mean temporal interval for the hand-foot task was significantly different ($p = 0.019$). This result is consistent with the idea that the simultaneity of hand-foot tapping is based on the timing of sensory feedback from tapping rather than other factors like motor commands.

Discussion

In this study, we aimed to elucidate the mechanism of simultaneous tapping in different body parts. First, we showed that bimanual tapping had high temporal precision and

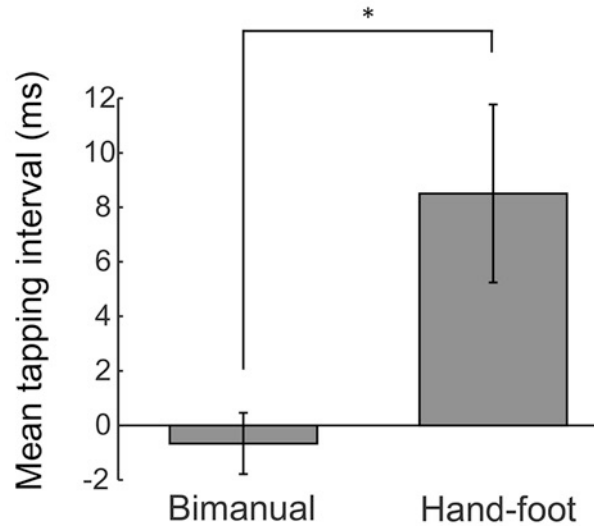


Fig. 4. Mean tapping interval in bimanual and hand-foot tapping tasks. In the bimanual condition, plus sign indicates right hand tapped earlier. Note that the result is normalized for the hand-foot condition so that the plus sign indicates that a foot tapped first. The error bars represent the standard error across participants ($*p < 0.05$).

both tactile and auditory sensory feedbacks could not provide enough sensory feedback to achieve such high temporal precision.

On the other hand, using a hand-foot simultaneous tapping task, we also showed that the simultaneity of hand-foot tapping was based on the timing of sensory feedback rather than other factors such as the timing of motor command production. We showed that tapping of the foot must precede that of the hand by about 8 ms on average for them to be perceived as simultaneous. This is comparable to the previously reported temporal difference (11.5 ms) between tactile stimuli to a hand and a foot required to be judged as perceptually simultaneous (Bergenheim, M., Johansson, H., Granlund, B., & Pederson, 1996). This suggests that simultaneous hand-foot tapping is almost completely based on the perceived temporal difference in sensory feedback.

Overall, our results suggest that the mean temporal interval of simultaneous tapping is dependent on sensory feedback, but the feedback is not precise enough to improve the temporal precision of tapping, thus simultaneity precision in trial-by-trial tapping might mostly reflect the precision of another neural process such as synergetic motor commands.

Acknowledgements

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THE IMPORTANCE OF VESTIBULAR INPUT AND THE ENVIRONMENT TO EARLY CHILD DEVELOPMENT AS DETERMINED THROUGH PSYCHOPHYSICAL PRINCIPLES

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Adaptation to the gravitational vector must be considered in the ecology of early child development. Proprioceptive/vestibular interactions occur as early as the first synapse in the brain. This interaction is a critical catalyst to the proper development and functioning, required for efficient learning and movement ability. The recent rise of sensory processing issues coinciding with demands for STEM literacy requires us to consider how recent cultural changes have impacted a child's natural experience within the gravitational vector and how changes driven by this interaction may be impacting the quality of future learning and movement ability. Viewing human development through the lens of psychophysical principles will illustrate the critical impact gravity has upon optimal sensory system function and physical development.

We will present a psychophysical model that demonstrates how gravity profoundly affects the form and function of human development. Sensory systems require gravity to function optimally and have critical periods for development. Core motor, sensory, perception and cognitive systems are in place and develop relatively rapidly after birth. Through a complex choreography of quantity and quality of experiences within the gravity vector a human develops the sensory processing systems necessary for efficiently navigating the psychosensory field and body field. Analyzing human development utilizing our knowledge of neural navigation architecture, planes of space, axis of motion and haptic awareness we can employ a psychophysical model providing a new platform for observing, measuring and analyzing human development.

Technological and medical advancements and an increasingly mobile society is affecting the natural trajectory of human development. Screen time replacing physical play, infants sleeping on backs instead of in prone, and restrictive devices including car seats all limit a child's mobility within the gravity vector. Repetition and intensity of stimuli is required for stabilizing neural pathways and hopefully reducing unnecessary redundant information. A lack of sufficient duration and intensity of biologic system experience within the gravity vector plausibly contributes to the rise in sensory processing and integration disorders, including dyslexias, attention deficit disorders and autism, conditions where information may be overwhelming and the child unable to inhibit the redundant information.

Psychophysical science is based upon the assumption that a quantitative relationship exists between environmental stimuli and sensory perception. Extending traditional Fechnerian principles to include the gravity vector and the development of biologic systems a new psychophysical model can be realized. This model presents the opportunity for new assessments, interventions, technologies and programs to address the rise in sensory processing issues and prepare young minds to thrive in a changing world demanding STEM literacy.