The Use of Timing Control Strategies to Overcome Severe Time Constraints during Rapid Interception

Tetsuya Ijiri, Masahiro Shinya, Kohtaroh Hagio and Kimitaka Nakazawa
Department of Life Sciences, Laboratory of Sports Sciences, The University of Tokyo, Komaba, Tokyo, Japan

Keywords: Baseball, Visuomotor Coordination, Startle Reaction, Acoustic Stimulation, Sports, Vision, Feedback, Feedforward, Efference Copy, Electromyography (Emg), Excitability, Subcortical, Motor Circuit.

Abstract: We investigated the mechanisms underlying timing of rapid interceptive actions under severe time constraints, such as those required in baseball, cricket, and tennis. To compensate for the temporal uncertainty of a moving target, participants were required to control their movement onset and/or duration. In Experiment 1, we tested how movement onset and/or duration are controlled under severe time constraints in a rapid baseball-simulation interceptive task. We found two distinct control strategies that modulated task performance. We also found that corrections to ongoing movements occurred more rapidly than had previously been reported. In Experiment 2, we used startling acoustic stimulation to investigate the detailed mechanisms underlying decisions about the timing of movement onset. Our findings indicate that the timing of movement onset is modified continuously via a subcortical motor circuit. Overall, our findings indicate that rapid movement decisions rely on a hybrid of feedforward and feedback control, allowing for the circumvention of severe time constraints during rapid interceptive actions.

1 INTRODUCTION

Elite athletes exhibit extremely high spatiotemporal accuracy during rapid interceptive action, such as the movements required to hit a moving ball in baseball, cricket, or tennis. In these sports, a ball may travel from its origin to the hitting point in less than half a second, and the hitting action takes approximately 200 ms (Gray, 2002a). Opponents attempt to maximize the spatial and temporal uncertainty, and so both the ball speed and trajectory are highly unpredictable. Despite these challenges, professional players are able to hit a ball with a spatiotemporal accuracy in the range of centimetres and milliseconds (Regan, 1992). To achieve a high level of accuracy in the timing of interceptive actions, both movement onset and duration must be precisely controlled.

Accurate control of movement onset and/or duration is difficult under the above-mentioned conditions because of the relatively long physiological delay required for processing sensory information. Visuomotor delay (VMD), which is the time period between a visually detectable event and the resulting observable response to the event, has been reported to range from 100 to 300 ms (Runigo et al., 2010); (Runigo et al., 2005); (Bootsma and Van Wieringen, 1990). This delay presents a challenge when making online corrections to one's swing duration under severe time constraints.

It is also difficult to pinpoint the exact onset of a movement command using visual information about a moving target. This is because motor commands are triggered by visual stimulus events that occur approximately 150 ms before movement onset (Marinovic et al., 2009) and there is no enough time for discriminating the difference of ball speed. Although players utilize opponent movements (See Müller and Abernethy, 2012 for a review) and knowledge about prior trial (Gray, 2002a); (Gray 2002b) to anticipate ball trajectory and speed, they are still at risk of incorrectly anticipating a movement resulting high demands of online correction. The mechanism that permits the circumvention of such time constraints remains unclear.

The main purpose of this study was to examine the control mechanisms underlying the timing of rapid interceptive actions, such as those that allow athletes to circumvent severe time constraints and achieve high temporal accuracy. We conducted two experiments wherein participants performed a

Ijiri T., Shinya M., Hagio K. and Nakazawa K..
The Use of Timing Control Strategies to Overcome Severe Time Constraints during Rapid Interception.
DOI: 10.5220/0004614100050012
In *Proceedings of the International Congress on Sports Science Research and Technology Support* (icSPORTS-2013), pages 5-12
ISBN: 978-989-8565-79-2

baseball-simulation rapid interceptive task, with faster and slower balls presented in a random order. In Experiment 1 we investigated the efficacy of strategies for controlling timing during rapid interception relative to task performance. We compared our experimental results with data regarding batters in actual baseball games, which had been recorded with a high speed camera. In Experiment 2 we used startling acoustic stimulation to examine the specific mechanisms that enable an individual to overcome the severe time constraints and plan their swing onset in response to various ball velocities (Carlsen et al., 2011); (Valls-Solé et al., 1999). This technique allowed us to investigate the temporal course of motor preparation.

2 EXPERIMENT 1

2.1 Materials and Methods

2.1.1 Participants

Twenty six healthy young males participated in the experiment (age range 18-24; mean = 20 years). All participants reported minimal experience with fast ball sports like baseball, cricket, or tennis, and stated they were right handed and had normal or corrected-to-normal vision. Ethical approval for this study was granted by the Ethical committee of The University of Tokyo and all participants provided informed consents.

2.1.2 Task and Apparatus

The experimental setup was shown in Figure 1. The participants were asked to intercept a moving virtual ball on a computer screen (23.6 inches, 1920 × 1080 pixels and a refresh frequency of 120 Hz) using a virtual arm that was controlled by the actual movement of their left elbow joint. Participants sat on a chair and placed their left forearm on a manipulandum. Movement of the manipulandum was calibrated such the degrees of rotation matched that of the virtual bat. A line that was horizontal to the axis of bat rotation was defined as the optimal hit point, and participants were encouraged to hit the ball at that point. When the participants set the bat at the initial position (e.g. -65 degrees from the optimal hit point), an auditory warning cue was given. After 500 ms, the ball was released downward. The participants were instructed to fully extend their elbow and to not stop the bat at the optimal hit point.

2.1.3 Procedures

The participants were exposed to two paired-speed conditions; 'Slow or Medium' and 'Medium or Fast', in which ball speeds varied between trials. Time-to-contact (TTC) was defined as the interval from ball release to the arrival of the ball at the optimal hit point. The TTC for the different conditions were 670 ms (Slow), 540 ms (Medium), and 410 ms (Fast). Participants completed 24 trials in each set and 4 sets in total for each condition. The control strategies used by each participant became stable in the second half of the 4 sets, and so the last 2 sets were regarded as the test sessions and included in the analysis. All the computerized events were controlled by a program written with LabVIEW software (National Instruments).

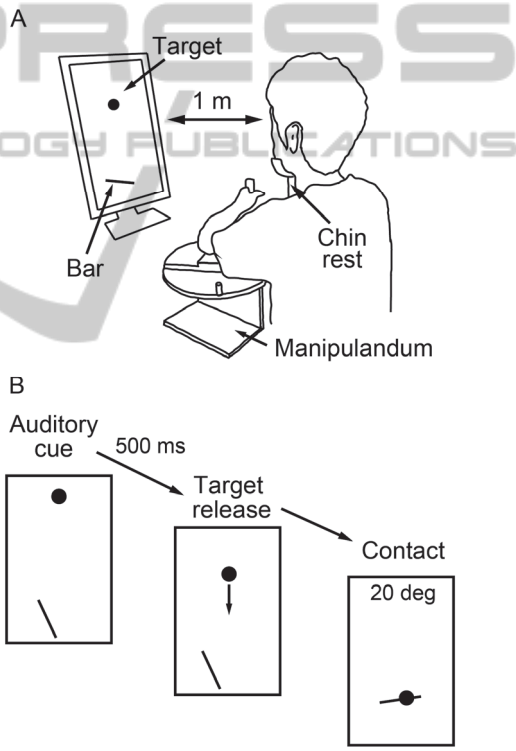

Figure 1: Experimental setup. (A) Physical set up. Using a manipulandum system, participants control the rotation of virtual bar projected of the monitor. (B) Virtual setup and time course of a trial. An auditory cue was provided, followed by 500 ms of foreperiod. The degree of the bar at the contact with the target was provided after every trial combined with visual feedback of the bar angle.

2.1.4 Data Reduction

Data were analysed offline using MATLAB (Mathworks) software and JMP10 (SAS Institute, NC, USA). The elbow angle data were digitally low-

pass filtered with a fourth-order, zero-phase-lag Butterworth filter at a cut-off frequency of 8 Hz.

To analyse the difference in control strategies between participants, we calculated swing onset and swing duration for each trial. The swing onset was defined as the time from ball release to the moment at which the angular velocity of the bat had reached 30 degrees/s and remained constant or surpassed this velocity for an additional 50 ms. The swing duration was defined as the time from swing onset to the moment at which the bat angle reached the optimal hit point. We also calculated delta onset, which was defined as the mean difference in swing onset between the faster and slower ball speeds. In addition, we calculated the delta duration, which was defined as the mean difference in swing duration between the faster and slower ball speeds.

To evaluate task performance, we analyzed constant error (CE) and variable error (VE) as indices of error direction and variability, respectively. The CE was defined as the difference between the TTC of the ball and the time at which the bat reached the optimal hit point (i.e. the sum of the swing onset and swing duration).

2.1.5 Recording Systems

The elbow angle data were measured using a potentiometer attached to the joint of the manipulandum. Electromyographic (EMG) signals were recorded via double differential surface electrodes (DE-3.1, Delsys) placed on the biceps brachii and triceps brachii of the left arm. The EMG signals were amplified (gain: 1000) using an EMG amplifier (BAGNOLI-8, Delsys). All data were digitally sampled at 1000 Hz using a program written with LabVIEW software.

2.1.6 Baseball Game Data

We recorded two baseball games: one at a university and one at a high school national tournament. Data were collected using a camera (Exilim EX-F1, Casio, Japan) with a frame rate of 600 fps. The camera was placed approximately 20 meters behind the batter and captured both the batter and pitcher in the same frame. We analysed a total of 41 trials, or instances where the batter swung at the ball, at the university game. At the high school game, we analysed a total of 39 trials.

The timing of ball release, swing onset, contact of the bat with the ball, and TTC of the pitched ball were analysed using image analysis software (MediaBlend, Japan). The timing of ball release and the contact point were easily detected by visual inspection. The timing of swing onset was defined as the time point at which a successive downward movement of the batter's hands was detected. TTC was defined as the time between the ball release and the contact between the ball and bat. To assess whether batters had a tendency to change their swing onset and/or swing duration according to perceived ball speed, we calculated Pearson's correlation coefficient between the TTC and the two variables.

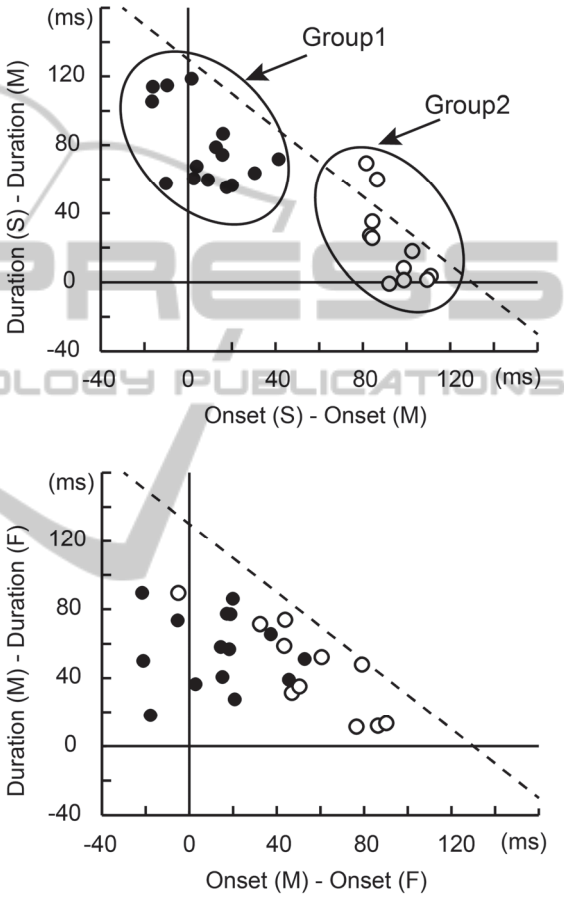

Figure 2: The distribution of delta onset and delta duration in slow or medium condition (top) and medium or fast condition (bottom) Diagonal dashed line represents optimal compensation of the 130 ms gap of TTCs. Control strategy in slow or medium condition was divided into two groups (filled circle: group1, open circle: group2). Similar tendency was observed in medium or fast condition.

2.2 Results

2.2.1 Different Control Strategies between Participants

The distribution of the delta onset and delta duration for all participants is shown in Figure 2. Using the Shapiro-Wilk normality test, we found that the

distribution of the delta onset in the 'Slow or Medium' condition was not normal distribution ($W = 0.87$, $p < 0.001$). Therefore, we divided the participants into two subgroups, as shown in the top panel of Figure 2. This tendency was also observed in the 'Medium or Fast' condition, as shown in the bottom panel of Figure 2. We compared the timing accuracy between these two groups.

2.2.2 Timing Accuracy

We compared the CE and VE of ball speed between the two groups using Welch's t-test. The significance level was set at 0.05 (fig. 3). The CE of group 1 was significantly higher than that of group 2 for the medium speed in the 'Slow or Medium' condition ($t = 4.33$, $p < 0.001$) and the fast speed in the 'Medium or Fast' condition ($t = 3.59$, $p < 0.001$). No significant differences were found in the other conditions (the slow speed in the 'Slow or Medium condition'; $t = 1.99$, $p = 0.059$, the medium speed in the 'Medium or Fast condition'; $t = 1.78$, $p = 0.089$).

The VE of group1 was significantly larger than that of group 2 for the slow speed in the 'Slow or Medium' condition ($t = 4.06$, $p < 0.001$) and in both speeds in the 'Medium or Fast' condition (Medium; $t = 2.78$, $p = 0.011$, Fast; $t = 2.50$, $p = 0.021$). There was no significant difference in the medium speed in the 'Slow or Medium' condition ($t = 1.44$, $p = 0.16$).

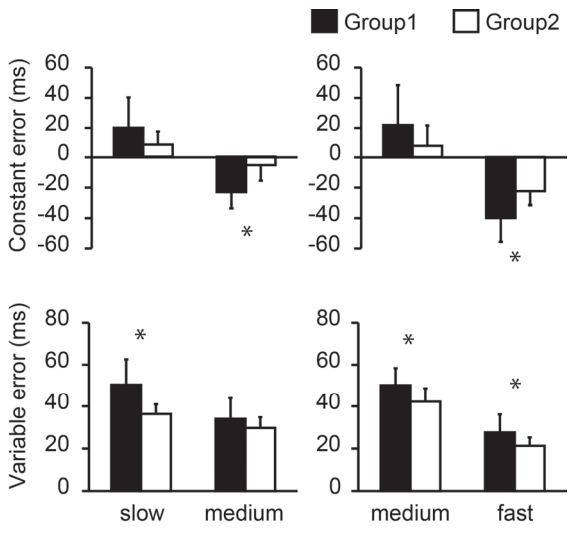

Figure 3: Constant error and variable error in paired-speed condition (filled bars: group1, open bars: group2). *p<0.05s, significant difference between groups. The error bars refer to ± 1SD.

2.2.3 EMG Latency for Online Correction

The participants in group 1 mainly modulated swing duration and not swing onset. We used EMG data to investigate the detailed mechanisms underlying online corrections in movement under the severe time constraint. Differences in control strategies were reflected in triceps brachii activity but not biceps brachii activity, so we analysed only the EMG data for triceps brachii. We sought to evaluate the time required to correct ongoing swing speed. The latency for online correction was defined as the time point of the first deviation from the averaged EMG amplitude between the faster and slower ball speeds, as shown in the top panel of Figure 4. To guide this measure, we calculated the time at which a significant difference in amplitude was observed for at least 15 ms. This was established using a successive t-test (p<0.05) that compared the averaged EMG amplitude of the two speeds. We also analysed the EMG onset in each trial, which was defined as the time point at which EMG activity increased by more than 3 SDs above baseline levels (the mean level during 100 ms of EMG activity collected before ball release).

The correction latency in the 'Slow or Medium' condition was 246.2 ± 16.7 ms, and the average EMG onsets in Group 1 for the slow speed and medium speed were 172.2 ± 76.6 ms and 174 ± 56.8 ms. The correction latency in the 'Medium or Fast' condition was 210.9 ± 20.8 ms, and the average EMG onsets in Group 1 for the medium speed and fast speed were 142.1 ± 69.2 ms and 135.5 ± 52.7 ms (bottom panel of fig. 4). Note that the time between EMG onset and the correction latency was approximately 70 ms in all conditions, and this value was much smaller than previously reported VMD. This suggests the involvement of internal feedback loops that integrate efferent and afferent signals (Wolpert et al. 1995) with negligible delay (discussed in the following section).

2.2.4 Behaviours of Baseball Batters

The correlation coefficient between swing onset and TTC was 0.82 ($p < 0.001$) and between swing duration and TTC was 0.53 ($p < 0.001$) in the high school game. In the university game, the correlation coefficient between swing onset and TTC was 0.60 ($p < 0.001$) and between swing duration and TTC was 0.29 ($p = 0.06$).

3 EXPERIMENT 2

In Experiment 1, the timing strategy for changing swing onset outperformed the strategy for changing

swing duration. Moreover, we were able to speculate about a mechanism that makes the correction of ongoing movement possible. However, the mechanism involved in modulating swing onset was still unclear. In Experiment 2, we sought to investigate the detailed control mechanisms involved in changing swing onset to adjust to different ball speeds.

Previous studies have reported that corticospinal excitability, measured using single-pulse transcranial magnetic stimulation (TMS), increases about 100 ms before EMG onset (Starr et al. 1988; McMillan et al. 2004). Although this excitatory drive (Floeter & Rothwell 1999) is modulated by a cortical inhibitory control mechanism (Nakamoto and Mori, 2012); (Reynolds and Ashby, 1999); (Soto et al., 2010), other inhibitory mechanisms involving subcortical motor circuits have been suggested (Maslovat et al., 2012); (Soto et al., 2010).

Startling acoustic stimuli (SAS) is a useful probe for pre-programmed motor commands and has been used to investigate the temporal course of motor preparation and subcortical motor circuit excitability. If a motor command is not prepared in advance (e.g. in a choice reaction time task), SAS does not facilitate any voluntary response relative to the task (Carlsen et al., 2004). However, in a simple reaction time task in which a motor command can be prepared in advance, SAS can elicit a voluntary response with a very short latency (Valls-Solé et al., 1999). In an anticipation-timing task, motor preparation occurs as late as 200 ms before response time (Carlsen and Mackinnon, 2010); (Carlsen et al., 2008).

We hypothesized that participants who predominantly changed their mainly swing onset in paired-speed condition would prepare a motor command and exhibit increased subcortical motor circuit excitability relative to faster ball speeds, regardless of actual ball speeds. If ball speed was slow, this subcortical motor circuit would be inhibited so as to prevent a motor command from being inaccurately timed. This would delay the "deadline" for decision making about speed discrimination, resulting in the circumvention of severe time constraints.

3.1 Materials and Methods

3.1.1 Participants

Six healthy male volunteers participated in the experiment (ages: 25.5 ± 1.5 years). All participants were right-handed, had normal or corrected-to-normal vision, and provided informed consent.

3.1.2 Task and Apparatus

The experimental task, apparatus, and recording methodology were identical to those in Experiment 1 except that a loud speaker (DSR 112, YAMAHA, Japan) was placed 50 cm behind the participants' heads. SAS was generated by a customized program written using LabVIEW software that produced broadband white noise (duration; 50 ms, rise time; 1 ms). The signal was amplified and presented at an intensity of 123±1 dB through the loudspeaker. EMG signals were obtained from electrodes placed on the triceps brachii (TB), biceps brachii (BB), and sternocleidomastoid (SCM). SCM activity was regarded as an indication of startle response.

3.1.3 Procedures

Experiment 2 consisted of two conditions; a paired-speed condition and a single-speed condition. The TTC in the paired-speed condition was Slow (800 ms) and Fast (500 ms), whereas the TTC in the single-speed condition were solely Slow (800 ms). We set the Slow TTC larger than in Experiment 1 to make changing one's swing onset relatively easy and thus ensure stable task performance.

Prior to the experimental session, participants performed a practice session in which they stabilised their timing strategies. The SAS was not presented in the practice session. Swing duration and bat angle at the moment of contact were provided as a feedback for each trial. All participants completed between 60 and 90 practice trials. Data from participants who mainly changed their swing duration were discarded because the aim of Experiment 2 was to investigate the detailed mechanisms involved in changing one's movement onset.

Following the practice session, each participant performed a total of 80 experimental trials. Participants were instructed to use the same strategy and swing duration as in the practice trials. In 8 Slow-speed trials (10% of all trials), the SAS was presented 150 ms after the moment of ball release. Note that the SAS was not presented in the Fast-speed trials.

Participants then performed 20 practice trials in the single-speed condition without the presentation of SAS. Finally, participants completed 80 experimental single-speed trials. In 8 trials, the SAS was presented 150 ms after the moment of ball release.

3.1.4 Data Reduction

EMG onset was analysed using the same algorithm as Experiment 1. The probability of startle response elicited by SAS was analysed with respect to SCM activity to evaluate the excitability of the subcortical motor circuit (Maslovat et al., 2012). SCM activity that occurred within 120 ms of the SAS presentation was regarded as a startle reflexive response. Similarly, the probability that a preprogrammed motor command had been triggered early was analysed in terms of TB activity to assess the state of advance motor preparation. EMG activity at the TB that occurred within 150 ms of the SAS presentation was regarded as an early release of preprogrammed motor command.

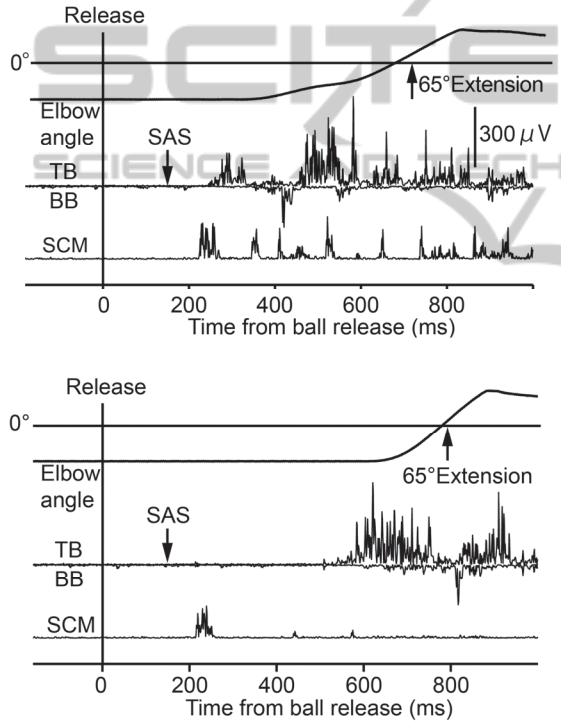

Figure 5: Typical EMG and elbow angle data from startle trials in paired-speed (top) and single-speed condition (bottom). SAS elicited both TB and SCM activities in paired-speed condition, but elicited only SCM activity in single-speed condition.

3.2 Results

3.2.1 Behaviour in Non-startle Trials

Swing durations in the non-startle trials were 223.6±24.8 ms for the Slow-speed trials and 184.5±15.5 ms for Fast-speed trials in paired-speed condition. The EMG onsets in the non-startle trials were 482.7±25.4 ms for the Slow-speed trials and 280.1±17.7 ms for the Fast-speed trials. These results indicate that SAS was presented 332.7 ms (for the Slow-speed condition) and 130.1 ms (for the Fast-speed condition) prior to TB activity onset.

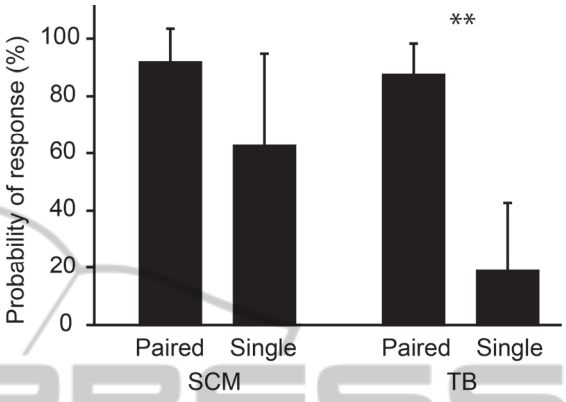

Figure 6: Probability of response in SCM and TB in paired and single-speed condition. $^{**}p<0.01$, significant difference in the value between paired and single-speed condition. The error bar refer to ±1 SD.

3.2.2 Response Probability of Startle Indicator

Typical responses in the startle and non-startle trials are illustrated in Figure 5. SAS in the paired-speed condition typically elicited early activity in both the SCM and TB, whereas SAS in the single-speed condition evoked activity in the SCM but not the TB.

The probability of a startle response elicited in the SCM by SAS was 94.4±10.1 % in the paired-speed condition and 75.0±31.6 % in the single-speed condition (left panel of Figure 6). A paired sample t-test did not reveal a significant difference between the response probability for the paired and single-speed conditions ($t = 1.56$, $p = 0.18$).

3.2.3 Probability and Latency of Early Release of Prepared Motor Command

The probability of early triggering of a prepared motor command in the TB was 86.1±8.6 % in the paired-speed condition and 16.7±20.4 % in the single-speed condition (right panel of Figure 6). A paired sample t-test revealed a significant difference between the probability of TB response in the paired and single-speed conditions ($t = 7.47$, $p < 0.01$).

The EMG onset of early triggered TB activity in the paired-speed condition was 239.5±11.3 ms (89.5 ms from SAS presentation).

4 DISCUSSION

4.1 Differences in Control Strategy

In Experiment 1, we found two main timing strategies. In group 1, participants mainly modulated their movement duration according to the speed of the ball, whereas in group 2, participants modulated their movement onset according to the speed of the ball with a fixed movement duration. However, participants did not exclusively control either their swing onset or swing duration. Rather, both swing onset and swing duration were flexibly modified, and the balance between these two variables was different among participants. In our observations of batters in high school baseball games, we found a significant correlation between both swing onset and TTC and between swing duration and TTC, indicating that these two variables are flexibly controlled.

The data from the present study are not sufficient to speculate about what distinguishes the two observed control strategies. However, we presume that individuals who mainly change their swing duration take relatively longer to discriminate ball speed than those who emphasise swing onset.

4.1.1 Differences in Task Performance

The task accuracy in group 2 was higher than that of group 1. Reasons for this difference might include the number of control variables involved in online correction and the short time period available for the correction. To correct an ongoing movement, the timing of correction and modified movement speed need to be considered together. On the other hand, only accurate timing of movement onset is required to change swing onset. Moreover, the time available for online correction was minimal given the time constraints in this study, even if it were possible to correct ongoing movement with a short delay (discussed in the next section).

4.1.2 Latency for Online Correction

The participants in Group 1 started their swing at the time required to accommodate faster ball speeds and modified their swing speed to adjust to slower ball speeds. The correction latency was about 70 ms from EMG onset in both conditions. This is much shorter than previously reported VMD values, which range from 100 to 300 ms (Runigo et al., 2010); (Runigo et al., 2005); (Bootsma and Van Wieringen 1990), but is comparable to a latency ranging from 83 to 122 ms reported by Higgins and Angel (1970) and 30 to 150 ms reported by Cooke and Diggles (1984). Therefore, the corrective response observed in this study can be accounted for not by sensory feedback loops but internal feedback loops (Wolpert et al., 1995). A forward model in the loops provides a reliable estimation of effector location and velocity by integrating efferent and afferent signals with negligible delays, and makes online correction possible for rapid and short movements (see Desmurget and Grafton, 2000 for a review). The observed correction latency in the present study indicates the contribution of internal feedback loops in the control of rapid interceptive movements.

4.1.3 Effect of SAS on Voluntary Response

In Experiment 2, SAS was presented in the slow-speed trials in both paired and single-speed conditions. However, the SAS consistently elicited TB activity in the paired-speed but not the single-speed condition (fig. 6). The timing of SAS presentation was 332.7 ms prior to EMG onset of TB in the slow-speed trial. Previous studies have reported that motor preparation is not complete until less than 200 ms before response time (Carlsen and Mackinnon, 2010); (Carlsen et al., 2008). Our participants appear to have prepared motor commands with respect to the timing of a fast-speed ball before discriminating the actual ball speed. When the ball speed is slow, subcortical motor circuit excitability might be inhibited so as to prevent a motor command from being inaccurately timed. We did not randomize the experimental order of the paired and single-speed conditions, and so did not eliminate the possible effect of habituation to the SAS (Maslovat et al., 2012). Further study is needed to clarify the influence of this confounding factor.

5 CONCLUSIONS

In summary, we have shown that a timing strategy in which both movement onset and duration were controlled outperformed a strategy in which movement duration was mainly modulated with less of an emphasis on onset. The rapid correction of ongoing movement likely involves internal feedback loops. Moreover, using startle acoustic stimulation, we have shown that modulation of excitability in subcortical motor circuits is likely involved in the continuous control of movement onset under severe time constraints.

REFERENCES

Bootsma, R. J. & Van Wieringen, P. C., 1990. Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance*, 16(1), pp.21–29.

Carlsen, A. N. et al., 2011. Considerations for the use of a startling acoustic stimulus in studies of motor preparation in humans. *Neuroscience and biobehavioral reviews*, 35(3), pp.366–76.

Carlsen, A. N. et al., 2008. Motor preparation in an anticipation-timing task. *Experimental brain research*, 190(4), pp.453–61.

Carlsen, A. N., Chua, R. & Inglis, J., 2004. Can prepared responses be stored subcortically? *Experimental brain research*, 159(3), pp.301–9.

Carlsen, A. N. & Mackinnon, C. D., 2010. Motor preparation is modulated by the resolution of the response timing information. *Brain research*, 1322, pp.38–49.

Cooke, J. D. & Diggles, V. A., 1984. Rapid error correction during human arm movements: evidence for central monitoring. *Journal of motor behavior*, 16(4), pp.348–63.

Desmurget, M. & Grafton, S., 2000. Forward modeling allows feedback control for fast reaching movements. *Trends in cognitive sciences*, 4(11), pp.423–431.

Floeter, M. K. & Rothwell, J. C., 1999. Releasing the brakes before pressing the gas pedal. *Neurology*, 53(4), pp.664–664.

Gray, R., 2002a. Behavior of college baseball players in a virtual batting task. *Journal of Experimental Psychology: Human Perception and Performance*, 28(5), pp.1131–1148.

Gray, R., 2002b. "Markov at the Bat": A Model of Cognitive Processing in Baseball Batters. *Psychological Science*, 13(6), pp.542–547.

Higgins, J. R. & Angel, R. W., 1970. Correction of tracking errors without sensory feedback. *Journal of experimental psychology*, 84(3), pp.412–6.

Marinovic, W., Plooy, A. M. & Tresilian, J. R., 2009. The utilisation of visual information in the control of rapid interceptive actions. *Experimental psychology*, 56(4), pp.265–73.

Maslovat, D., Carlsen, A. N. & Franks, I. M., 2012. Subcortical motor circuit excitability during simple and choice reaction time. *Behavioral neuroscience*, 126(3), pp.499–503.

McMillan, S., Nougier, V. & Byblow, W., 2004. Human corticospinal excitability during a precued reaction time paradigm. *Experimental brain research*, 156(1), pp.80–7.

Müller, S. & Abernethy, B., 2012. Expert anticipatory skill in striking sports: a review and a model. *Research quarterly for exercise and sport*, 83(2), pp.175–87.

Nakamoto, H. & Mori, S., 2012. Experts in fast-ball sports reduce anticipation timing cost by developing inhibitory control. *Brain and cognition*, 80(1), pp.23–32.

Regan, D., 1992. Visual judgements and misjudgements in cricket, and the art of flight. *Perception*, 21(1), pp.91–115.

Reynolds, C. & Ashby, P., 1999. Inhibition in the human motor cortex is reduced just before a voluntary contraction. *Neurology*, 53(4), pp.730–5.

Runigo, C. Le, Benguigui, N. & Bardy, B. G., 2005. Perception-action coupling and expertise in interceptive actions. *Human movement science*, 24(3), pp.429–45.

Runigo, C. Le, Benguigui, N. & Bardy, B. G., 2010. Visuo-motor delay, information-movement coupling, and expertise in ball sports. *Journal of sports sciences*, 28(3), pp.327–37.

Soto, O., Valls-Solé, J. & Kumru, H., 2010. Paired-pulse transcranial magnetic stimulation during preparation for simple and choice reaction time tasks. *Journal of neurophysiology*, pp.1392–1400.

Starr, A. et al., 1988. Enhancement of motor cortical excitability in humans by non-invasive electrical stimulation appears prior to voluntary movement. *Electroencephalography and clinical neurophysiology*, 70(1), pp.26–32.

Valls-Solé, J. et al., 1999. Patterned ballistic movements triggered by a startle in healthy humans. *The Journal of physiology*, 516, pp.931–8.

Wolpert, D. M., Ghahramani, Z. & Jordan, M., 1995. An internal model for sensorimotor integration. *Science*, 269(5232), pp.1880–1882.