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# Keeping your eye on the target: eye–hand coordination in a repetitive Fitts' task

S. de Vries[1] · R. Huys[2] · P. G. Zanone[2]

## Abstract
In a cyclical Fitts' task, hand movements transition from continuous to discrete movements when the Index of Difficulty (ID) increases. Moreover, at high ID (small target), the eyes saccade to and subsequently fixate the targets at every movement, while at low ID (large target) intermittent monitoring is used. By hypothesis, the (periodic) gaze shifts are abandoned for movement times shorter than about 0.350 s due to systemic constraints (i.e., a refractory period and intrinsic latency). If so, the transition in eye and hand movements is independent. To investigate these issues, the present study examined the effects of changing ID via the targets' width or distance as well as hysteresis in eye–hand coordination. To this aim, 14 participants performed a cyclical Fitts' task while their hand and eye movements were recorded simultaneously. The results show that the transition in eye–hand synchronization (at 2.87 bit; 0.25 s) and in hand dynamics (at 4.85 bit; 0.81 s) neither co-occurred nor correlated. Some small width vs. distance dissociations and hysteresis effects were found, but they disappeared when eye–hand synchronization was viewed as a function of movement time rather than ID. This confirms that a minimal between-saccade time is the limiting factor in eye–hand synchronization. Additionally, the timing between the start of the hand movement and the saccade appeared to be relatively constant (at 0.15 s) and independent of movement time, implying a constant delay that should be implemented in a dynamical model of eye–hand coordination.

**Keywords** Fitts' task · Coordination · Eye–hand · Synchronization · Cyclical movement · Gaze behavior

## Introduction

The coordination of hand and eye movements is fundamental in the control of accurate goal-directed movements and has been a topic of scientific interest since Woodworth's (1899) seminal development of his two-component model. Accordingly, movements towards a target are composed of an initial impulse and a subsequent correction phase. In this latter phase, visual feedback is used to adjust the movement and to accurately reach the target. Though Woodworth's original study involved cyclical movements, most research on eye–hand coordination has involved discrete movements. In

that context, gaze initiation always precedes hand movement initiation and arrives at the target concurrently with hand peak acceleration, that is, well before the hand reaches the target (Binsted et al. 2001). However, various studies suggest that discrete and cyclical movements are differentially organized (e.g., Guiard 1993; Huys et al. 2008, 2015; van Mourik and Beek 2004) and that gaze behavior in cyclical movements is not simply a concatenation of discrete movements (e.g., Terrier et al. 2011).

Reciprocal, but also discrete, aiming movements are often investigated in a Fitts' task (Fitts 1954; Fitts and Peterson 1964). The corresponding results robustly show that movement time (MT) increases when task difficulty increases, following what is now known as Fitts' law, $MT = a + b \times ID$, where $a$ and $b$ are the adjustable constants, and ID represents the task's index of difficulty. The ID is defined as the amount of information (in bits) that is required to specify target width ($W$) relative to distance ($D$) and is quantified as $ID = \log_2\left(\frac{2D}{W}\right)$. To reflect what participants actually do, rather than the task demands, the effective

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ID is often computed as the mean distance between movement reversals and effective W as 4.133 times the SD of the reversals (see, e.g., MacKenzie 1992; Welford 1968).

According to Fitts' law, it should be irrelevant whether ID is changed via D or W. In practice, changes in D and W, however, affect MT differently (e.g., Huys et al. 2015; Meyer et al. 1988; Sheridan 1979; Welford et al. 1969), even though the differences are marginal and the linear relation between ID and MT has been proven to be robust under multiple conditions (MacKenzie 1992). Fitts' law also holds for saccadic eye movements (Abrams et al. 1989), albeit only when D is scaled. Indeed, saccades show a fixed relation between amplitude and duration and thus act as if a constant W is used (Harris and Wolpert 2006, see also; Wu et al. 2010).

When a task's ID is increased by decreasing W, next to an increase in MT, at a critical ID, the hand movements go through a bifurcation: the movements shift from a cyclical unit of action to a concatenation of discrete movements between fixed points (saddles, to be precise; see Huys et al. 2010; Knol et al. 2017). Further, a change in accuracy constraints also influences the need for visual information to control the hand movements. Bootsma et al. (2002) showed how the importance of visual information changes with the ID by manipulating the availability of visual information. Their participants performed a cyclic Fitts' task while wearing goggles that opened and closed at regular intervals, allowing the participants to organize their movements so as to 'choose' which part of their movements they could see. The availability of visual information was further manipulated by varying the ratio between the duration when the goggles were open vs. closed. At low ID (ID = 4), reduced availability of visual information increased MT and rendered the movements moderately more nonlinear. The timing of the movements relative to the opening and closing of the goggles was only minimally affected, however. In contrast, at high ID (ID = 6) the changes in MT and the movement kinematics were more pronounced, and the movement became timed in a way that allowed the participants to view their homing in-phase towards the targets. Thus, the availability of visual information, and the part of the trajectory perceived, is less important for low ID than it is for high ID.

The reduced need for visual information at low ID is also apparent from the lower saccade rate during fast cyclical movements. Lazzari et al. (2009), investigating eye–hand coordination in a cyclic Fitts' task, found that at low ID, when MT was less than 0.350 s, eye–hand coordination switched from continuous monitoring to a control in which saccades were made only intermittently. For MTs longer than 0.350 s, each hand movement was accompanied by a saccade, after which the eyes fixated the target. Lazzari et al. hypothesized that, due to systemic constraints—relating to an average refractory period of 0.200 s between two saccades (Jürgens et al. 1981) and

an intrinsic latency of 0.150 s necessary for information pickup (Gowen and Abadi 2005)—beyond a certain point, the eyes simply cannot keep up with the oscillation rate of the hand, which forces the system to adopt an intermittent visual monitoring.

If the transition to intermittent monitoring is indeed due to systemic constraints, eye–hand coordination is by implication governed predominantly by context-independent factors. Indeed, the suggested constraints depend only on MT and not on movement history or accuracy demands. In support of this implication, Lazzari et al. (2009) found that eye–hand coordination varies more lawfully with MT than with ID. However, in their study, they only changed target width while target distance was fixed and they did not study potential hysteresis effects. In a system with hysteresis, the current state of the system not only depends on the bifurcation (or control) parameter (Strogatz 1994; Haken 1983), but also on its previous state(s). For hand movements, hysteresis has been reported in the cyclic Fitts' task (e.g., Buchanan et al. 2004) and the effects of changing D or W to get the same ID can be differentiated (e.g., Huys et al. 2015). These effects might not only be visible in the hand's movement organization, but also in the eye–hand coordination. If so, this would indicate that eye–hand coordination is not (stringently) constrained by a context-independent systemic limit but follows a more complex dynamical organization.

In the present study, we addressed these issues by replicating and extending the study of Lazzari et al. (2009) by simultaneously recording hand and eye movements in a cyclic Fitts' task. By either increasing or decreasing the ID stepwise, we aimed to investigate a possible hysteresis effect. Further, by comparing effects of changing either W or D, we investigated whether they differentially affected the eye–hand coordination.

# Method

## Participants

After giving their informed consent, 16 participants (age 23–60 years, 12 male and 4 female) volunteered in the experiment. All had normal or corrected to normal vision, had no known neurological, motor, or coordination impairments, and 15 out of the 16 participants were right-handed. The experiment was approved by the local institution's ethical board. Two participants were unable to finish the experiment due to technical issues and eye irritation; their data were therefore excluded from further analysis, leaving data of 14 participants (age 23–60 years, 11 male and 3 female) to be analyzed.

## Materials

Participants were seated at a desk on an office chair behind a $60.0 \times 33.8$ cm monitor (resolution: $1920 \times 1080$). To minimize head movements, participants rested their head on a chinrest during each trial. The chinrest was place at 60 cm from the monitor, such that 1 cm on the monitor equaled $\sim 1°$ of the visual field. Eye movements were recorded with the ISCAN etl-200 (ISCAN, inc.), an infrared corneal reflection device. The participants made sliding movements with a hand-held stylus (18 g, $156.5 \times 14.9$ mm, $\sim 1$ mm tip) on a digitizer tablet (WACOM INTUOS4 XL tablet). The corresponding movements were rendered on the monitor at 60 frames/s. Eye and hand movements were recorded at 240 and 133 Hz, respectively. Only the horizontal component of these movements was used in the analysis.

## Procedure

Participants performed a cyclical Fitts' task. Two black bars were presented over the entire height of the screen against a grey background. The position of the tip of the pen on the tablet was rendered as a red dot (1.5 mm diameter) on the screen. The participants were instructed to make back and forth movements between the two targets as fast and accurately as possible.

The ID was stepwise increased from 2.0 to 6.0 or decreased from 6.0 to 2.0, with changes occurring after every 25th back-and-forth movement. As Lazzari et al. (2009) reported that the transition from intermittent to continuous monitoring occurred around an ID of about 3.0, ID increments around this value were chosen to be smaller. Nine different IDs were used, namely 2.0, 2.5, 2.8, 3.2, 3.5, 4.0, 4.5, 5.0, and 6.0. These IDs were created by changing the $W$ from 0.47 to 7.0 cm while keeping $D$ constant at 15 cm or by changing the $D$ from 2.0 to 32.0 cm while keeping $W$ fixed at 1.0 cm. This way, four different conditions were created: increasing ID by width scaling ($W_{up}$), decreasing ID by width scaling ($W_{down}$), increasing ID by distance scaling ($D_{up}$), and decreasing ID by distance scaling ($D_{down}$).

One block consisted of the nine ID-steps of 25 movement cycles each. Each block was performed three times so that 12 blocks were performed in total. Each participant performed these blocks in randomized grouped order (i.e., all conditions were performed once before the next repetition of a condition had to be performed). Between blocks, participants were given the opportunity to take a rest.

Before the experiment proper, each participant performed a practice condition in which randomized $W$s and $D$s were used to get familiarized with the experimental set-up. The eye tracker was calibrated via a standard procedure before starting the measurements. During this procedure, participants looked at 9 targets (separated by 20 cm horizontally

and 12 cm vertically) on the screen. The resulting data were used to scale the data of the experiment proper. The total experiment took approximately 90 min.

## Data processing

The hand position time series were filtered, using a dual-pass 5th order Butterworth filter with a cutoff frequency of 8 Hz, and differentiated to get velocity and acceleration time series. For the eye-tracker data, more extensive processing was necessary to prepare the data for analysis. Thereto, a customized script was written in Matlab™, to remove trends, outliers and high-noise segments from the data, replace and interpolate missing data, and rescale the data with use of the calibration procedure. The data were then filtered with a fifth order dual-pass Butterworth filter with a cutoff frequency of 30 Hz. Filtered eye-position data were differentiated to get velocity data. Eye movements were defined as saccadic if the velocity of the eye movement was greater than 30 cm/s and the point of gaze changed more than 0.6 times the inter-target-distance (i.e., the distance between the inner borders of the left and right target). Note that with this definition, only the primary saccades were included in our analysis. The start and end of the saccade were determined as the points where the position signal changed direction. Due to noise in the signal, directional change occurred immediately after a saccade and dwell time was not included in saccade duration. Saccades for which the unfiltered data had more than 25% missing values were excluded from further analysis. Finally, all saccades were subjected to visual inspection after which divergent saccades were removed from further analysis.

When the ID is changed during an ongoing cyclic Fitts' task, the hand movement rapidly adjusts to the new ID (Fernandez et al. 2006). To avoid transients, we excluded the first four movement cycles following each ID change from the analysis.

## Analysis

The MT was calculated as the time between consecutive hand departures from the target (i.e., half a movement cycle). The movement continuity (MC) was quantified by computing the ratio of acceleration at the reversal point and at peak acceleration (e.g., Buchanan et al. 2006; Guiard 1993, 1997; Mottet et al. 2001). MC ranges between 0 (no acceleration at the reversal point) and 1 (maximum acceleration at the reversal point) and is associated with discrete and continuous movements, respectively.

We quantified eye–hand synchronization as the ratio of the number of eye to hand movements, the $E/H$ ratio, for each ID step. This ratio indicates to which degree the eye 'follows' the hand movements. If a saccade is made for each

**Fig. 1** Movement time as a function of effective Index of Difficulty ($ID_e$). Plotted data are averaged over repetitions and participants, per trial ($n = 9$, per condition). The plotted lines are the results of linear regression of MT on $ID_e$, resulting in MT $= -0.51 + 0.28\,ID_e$ in the *D* condition and MT $= -0.85 + 0.35\,ID_e$ in the *W* condition
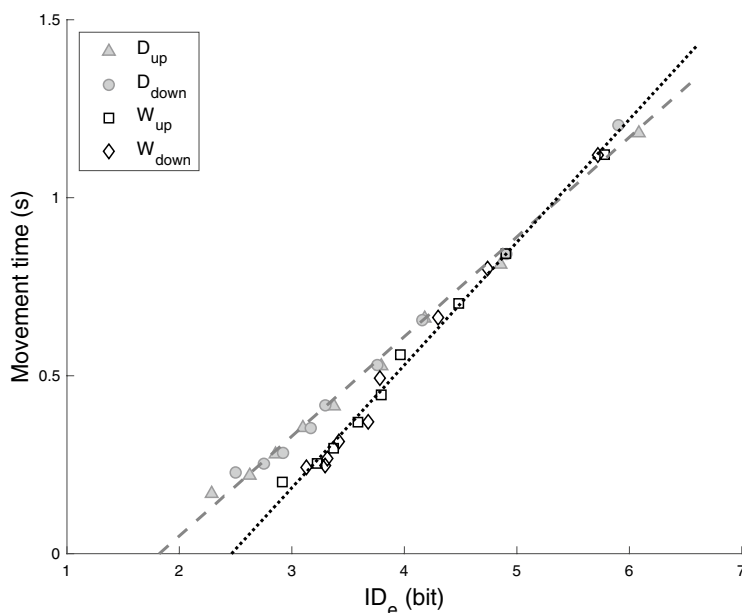


hand movement, *E*/*H* ratio = 1 (i.e., there is a one-to-one relation between hand and eye movements). Because only primary saccades were used in the analysis, the *E*/*H* ratio was maximally one. In addition, we investigated the timing of saccades relative to the corresponding hand movements. Thereto, we analyzed the onset latency (OL) between hand and eye movements as the interval between the hand departure from a target and the start of the corresponding eye movement.[1] In computing the OL, two trials had to be excluded from the analysis due to eye-tracker—tablet synchronization failure. Visual inspection led to the removal of 1647 saccades (i.e., 3.7% of the total number of saccades), leaving a total of 166 trials with a total of 42,950 saccades.

## Results

### Hand kinematics

#### Fitts' law and kinematics

We first verified whether Fitts' law applied to our data. Participants performed the task satisfactorily, with an average of 6.7% of missed aimings. To take into account the

participants' effective performance, we used the effective index of difficulty ($ID_e$) in the calculation of Fitts' law. We performed stepwise linear regression with dummy variables for condition (*W* vs. *D*) and direction (up vs. down) to regress the averaged MT over participants and repetitions (range: 0.17–1.20 s) against the averaged $ID_e$ (range: 2.3–6.1 bit; $n = 36$) and to compare slopes and intercepts (Andrade and Estévez-Pérez 2014; Motulsky and Christopoulos 2004). Including direction did not yield a significant improvement of the model (intercept: $p = 0.181$, slope: $p = 0.108$), suggesting the absence of hysteresis on *MT*. Therefore, direction was not included as a predictor in the regression model. The resulting model showed that Fitts' law applied to our data ($F(4,32) = 1410$, $p < 0.001$; $R^2 = 0.99$). In addition, the conditions differed significantly in slope ($F(1,32) = 45.35$; $p < 0.001$; $\eta p^2 = 0.59$) and intercept ($F(1,32) = 88.16$; $p < 0.001$; $\eta p^2 = 0.73$). This occurred because the *MT* for low *ID*s was shorter when *W* was large compared to when *D* was small (see Fig. 1).

We computed the average MC (over three trial repetitions) per participant as a function of $ID_e$. As can be seen in Fig. 2, for low $ID_e$, MC was close to 1, while for high $ID_e$, MC approached 0. The $ID_e$ value at which MC = 0.5 can be regarded as separating continuous and discrete movements. We identified this value using nonlinear regression with MC as dependent variable and $ID_e$ as independent variable according to the logistic function MC $= 1/(1 + e^{a \times ID_e + b})$ (Buchanan et al. 2006; Lazzari et al. 2009; Mottet et al. 2001). The critical value where MC = 0.5 is equal to $-b/a$ in this formula. For each experimental condition, the logistic function adequately represented the data (Table 1). Using an *F* test to compare the regression models (Motulsky and Christopoulos

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[1] Determining the corresponding eye movement is somewhat arbitrary at low IDs, when only few eye movements are made that are (at best) weakly phase locked to the hand movements only. We chose a limit of MT + 0.2 s for determining which hand movement a saccade belongs to. Thus, if eye movement was initiated more than 0.2 s after the hand had already arrived at the target, the gaze was considered as being early for the next movement, instead of being late for the previous one.
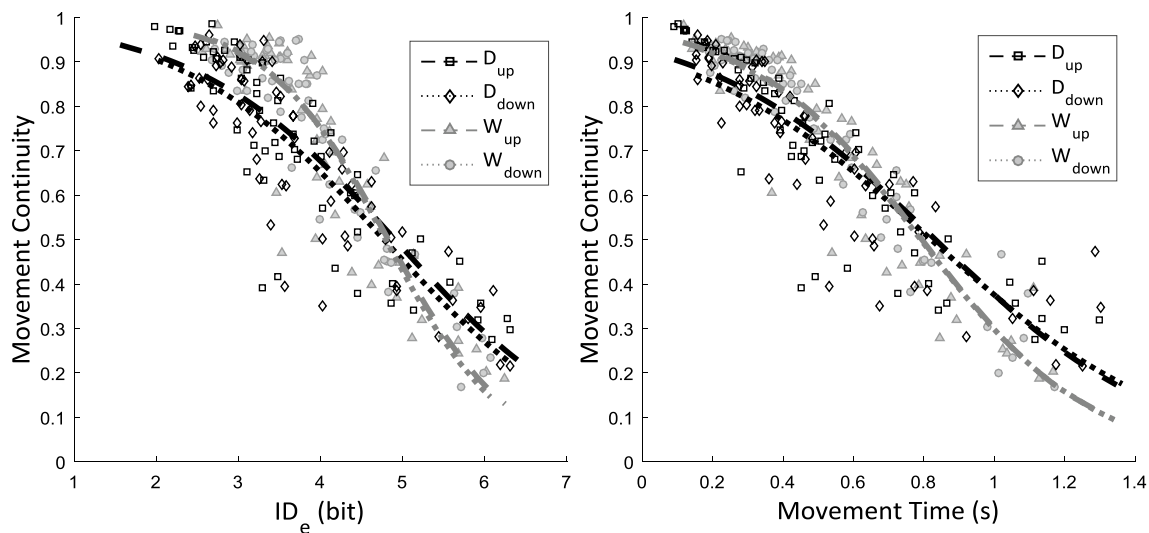
**Fig. 2** Movement continuity as a function of effective Index of Difficulty (ID$_e$; left panel) and as a function of movement time (MT; right panel). For clarity, data of only half the participants ($n = 7$) is shown and plotted values are averaged over trial repetitions. Regression lines are based on data of all participants ($n = 14$)

**Table 1** Results of the nonlinear regression of MC and *E/H* ratio against MT and ID

| Condition | Group analysis | | | | Individual analysis | | | |
|---|---|---|---|---|---|---|---|---|
| | MC | | *E/H* ratio | | MC | | *E/H* ratio | |
| | $R^2$ | Critical value | $R^2$ | Critical value | $R^2$ (mean ± SD) | Critical value (mean ± SD) | $R^2$ (mean ± SD) | Critical value (mean ± SD) |
| As a function of ID$_e$ | | | | | | | | |
| $D_{up}$ | 0.73 | 4.91 bit | 0.65 | 2.74 bit | 0.796 ± 0.117 | 4.84 ± 0.46 bit | 0.627 ± 0.151[a] | 2.62 ± 0.35 bit[a] |
| $D_{down}$ | 0.70 | 4.80 bit | 0.46 | 2.47 bit | | | | |
| $W_{up}$ | 0.78 | 4.85 bit | 0.64 | 3.20 bit | 0.835 ± 0.069 | 4.84 ± 0.31 bit | 0.645 ± 0.153 | 3.10 ± 0.35 bit |
| $W_{down}$ | 0.77 | 4.84 bit | 0.43 | 3.08 bit | | | | |
| As a function of MT | | | | | | | | |
| $D_{up}$ | 0.79 | 0.84 s | 0.89 | 0.25 s | 0.847 ± 0.084 | 0.82 ± 0.125 s | 0.909 ± 0.078 [a] | 0.25 ± 0.035 s [a] |
| $D_{down}$ | 0.77 | 0.81 s | 0.83 | 0.24 s | | | | |
| $W_{up}$ | 0.85 | 0.80 s | 0.87 | 0.25 s | 0.920 ± 0.037 | 0.80 ± 0.090 s | 0.901 ± 0.071 | 0.26 ± 0.029 s |
| $W_{down}$ | 0.90 | 0.79 s | 0.83 | 0.25 s | | | | |

Critical values where MC = 0.5 or *E/H* ratio = 0.5 are also shown. For the group analysis, averaged data over repetitions per participant was used ($n = 126$; all $p$s < 0.001). For the individual analysis, regression was performed on data from 14 individual participants, with *up* and *down* conditions combined ($n = 54$); mean ± SD of the resulting regressions are shown (all $p$s < 0.05)

*D* distance condition, *W* width condition, *ID$_e$* effective Index of Difficulty, *E/H* ratio eye-over-hand frequency ratio, *MC* movement continuity, *MT* movement time

[a]$n = 13$

2004), similar to the regression of MT on ID$_e$, the difference between the *W* and *D* conditions appeared significant ($F(2,500) = 57.74$, $p < 0.01$, $\eta p^2 = 0.19$). However, in both the *W* and *D* conditions there was no difference between the directions of change and thus, again, no sign of hysteresis (*W*: $F(2,248) = 0.13$, $p = 0.880$, $\eta p^2 < 0.01$; *D*: $F(2,248) = 1.32$, $p = 0.070$, $\eta p^2 = 0.01$). The difference in critical values was quite small (< 0.1 bit).

Following Lazzari et al. (2009), we also regressed MC as a function of MT. Again, the logistic function accurately captured the data (Table 1). The comparison between conditions revealed a difference between the *W* and *D* conditions ($F(2,500) = 28.45$, $p < 0.001$, $\eta p^2 = 0.10$), but not for the direction of change (*W*: $F(2,248) = 0.08$, $p = 0.922$, $\eta p^2 < 0.01$; *D*: $F(2,248) = 1.13$, $p = 0.324$, $\eta p^2 = 0.01$). Though the models for the *W* and *D* conditions remained
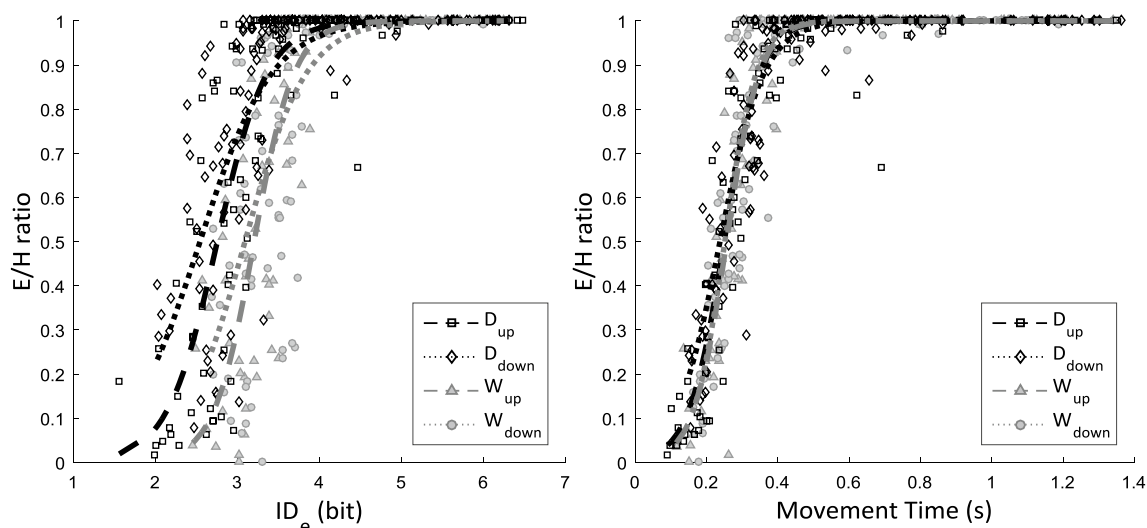
**Fig. 3** Eye-over-hand frequency ratio (*E/H* ratio) as a function of effective Index of Difficulty (ID$_e$; left panel) and as a function of movement time (MT; right panel). Presented data are averaged over trial repetitions

different, Fig. 2 shows that these differences were smaller, and the explained variance was higher, when MC was expressed as a function of MT than as a function of ID$_e$ (Table 1). When scaling *W*, the critical MT was slightly lower than when scaling *D*.

### Eye–hand coordination

To study the eye–hand coordination, we examined the *E/H* ratio, which equals 1 if a saccade is made for each hand movement and 0 if no saccades are made, and the timing of eye and hand movements. As expected, the *E/H* ratio was 1 for high ID values and decreased when the ID decreased below 4. We again used nonlinear regression to fit *E/H* ratio to a sigmoid with ID$_e$ as independent variable (Fig. 3). Again, for each scaling condition, the sigmoid adequately represented the data (all *p*s < 0.001; see Table 1). In addition, the difference between the *W* and *D* conditions was significant ($F_{(2,500)} = 54.27$, $p < 0.01$, $\eta p^2 = 0.18$), as was the difference between $D_{up}$ and $D_{down}$ conditions ($F_{(2,248)} = 4.56$, $p = 0.011$, $\eta p^2 = 0.04$), but not between $W_{up}$ and $W_{down}$ conditions ($F_{(2,248)} = 2.55$, $p = 0.080$, $\eta p^2 = 0.02$). The critical ID$_e$ value for *E/H* ratio was lower for the *D* scaling than for the *W* scaling and critical values for the conditions with decreasing ID were lower than for conditions with increasing ID. The explained variance for the former was lower than for the latter, though, rendering the computed critical values less reliable.

The *E/H ratio* represented as a function of MT (Fig. 3; Table 1) explained more variance than when represented as a function of ID$_e$. When represented as function of MT, the differences between scaling conditions disappeared (*W* vs. *D:* $F_{(2,500)} = 1.351$, $p = 0.260$, $\eta p^2 = 0.01$; $W_{up}$ vs.

$W_{down}$: $F_{(2,248)} = 1.207$, $p = 0.301$, $\eta p^2 = 0.01$), though the models for the $D_{up}$ and the $D_{down}$ condition remained slightly different ($F_{(2,248)} = 5.159$, $p = 0.006$, $\eta p^2 = 0.04$). The critical *MT* values for *E/H ratio* were practically the same in all conditions (< 0.01 s difference).

To examine whether the critical values for the hand and eye movements correlated, we computed these values based on individual participants' data using the nonlinear regression as before. To increase the number of data points, we combined the $W_{up}$ and $W_{down}$ conditions and the $D_{up}$, and $D_{down}$ condition per participant (providing 2 × 54 points per participant). One participant never achieved an *E/H* ratio below 0.5 under the *D*-scaling conditions; the corresponding data were not included in the individual analysis. The sigmoidal could be adequately fit as a function of both ID$_e$ and MT (as independent variables) for both MC and *E/H* ratio (dependent variables) for all participants (all *p*s < 0.05). The critical ID values and critical MT values were computed for both MC and *E/H* ratio (Table 1).

To compare the critical values between MC and *E/H* ratio and to compare critical values between conditions, two separate 2 × 2 repeated measures ANOVAs with condition (*D* vs. *W*) and measure (MC vs. *E/H* ratio) as within-subject factors and critical *ID* and critical *MT* as dependent factor revealed that critical values for *MC* were significantly and markedly lower than those for *E/H* ratio (ID: $F_{(1,12)} = 254.8$, $p < 0.001$, $\eta p^2 = 0.995$; MT: $F_{(1,12)} = 310.2$ $p < 0.001$, $\eta p^2 = 0.963$). Moreover, no significant (Pearson) correlation was found between critical values for *E/H ratio* and for *MC* (Table 2). Thus, the transition from continuous to intermittent visual tracking is independent from the transition from continuous to discrete hand movements.

**Table 2** Pearson correlations of critical $ID_e$ and critical *MT* between experimental conditions, using critical values obtained by fitting a logistic function through MC and *E/H* ratio for individual participants (see text)

| Dependent variable | Condition | Critical $ID_e$ | | Critical MT | |
|---|---|---|---|---|---|
| | | *E/H* ratio | MC | *E/H* ratio | MC |
| | | *D* | *W* | *D* | *W* |
| EH | *W* | 0.773[a,*] | 0.280[b] | 0.843[a,**] | −0.051[b] |
| MC | *D* | 0.114[a] | 0.957[b,**] | −0.128[a] | 0.896[b,**] |

*D* distance condition, *W* width condition, $ID_e$ effective Index of Difficulty, *E/H ratio* eye-over-hand frequency ratio, *MC* movement continuity; MT = movement time

\*$p < 0.05$; \*\*$p < 0.001$

[a]$n = 13$

[b]$n = 14$

Regardless, the ANOVA revealed a significant effect of condition ($F(1,12) = 27.79$, $p < 0.001$, $\eta p^2 = 0.698$) and a significant interaction ($F(1,12) = 26.58$, $p < 0.001$, $\eta p^2 = 0.689$), when comparing the critical ID values between the *D* and *W* condition, implying that the transition from continuous to intermittent monitoring occurs at lower ID when it is changed via *D* than via *W* (see also Table 1).

Similar to the group analysis, these differences disappeared when the critical value was expressed as a critical *MT* rather than as a critical $ID_e$ (condition: $F(1,12) = 1.504$, $p = 0.244$, $\eta p^2 = 0.111$; Interaction: $F(1,12) = 2.480$, $p = 0.141$, $\eta p^2 = 0.171$). In addition, a significant positive correlation was found between the critical values in the *W* and *D* condition, for both the *E/H* ratio and MC (see Table 2). Thus, participants that switched from intermittent to continuous monitoring at higher $ID_e$ and at higher *MT* in one condition also switched at higher $ID_e$ in the other condition.

### Eye–hand onset latency

Figure 4 displays the *OL*s against their corresponding *MT*, showing that the *OL* is about constant for all *MT*s (mean OL = 0.154 ± 0.054 s). For further analysis, the mean *OL* and *MT* per trial were computed, which were then averaged over repetitions and participants, resulting in 9 values per condition, that is, one value for each ID-trial in each of the four experimental conditions. There was no (Pearson) correlation between OL and MT ($r = 0.186$, $p = 0.277$), confirming that *OL* is indeed independent of *MT*. A 2 × 2 repeated measures ANOVA with condition (*D* vs. *W*) and direction (up vs. down) as within-subject factors and the averaged *OL* as dependent factor revealed no effect of scaling condition ($F(1,8) = 2.34$, $p = 0.164$, $\eta p^2 = 0.23$) or direction
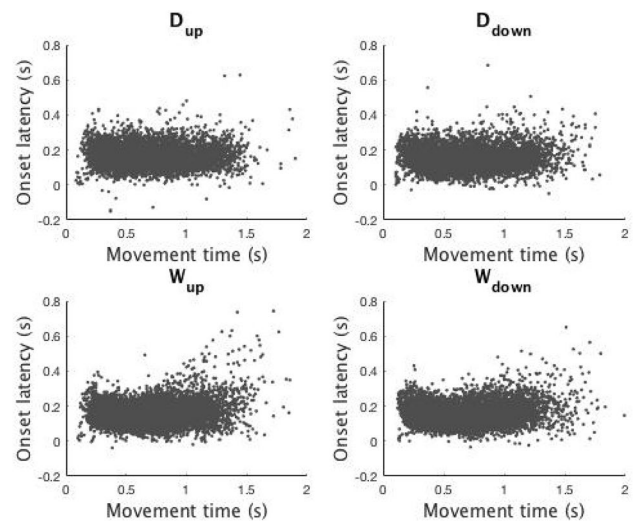


**Fig. 4** Onset latency of eye movements relative to start of the hand movement as a function of movement time for all experimental conditions. $D_{up}$, $n = 9753$ (m: 0.16 ± 0.05 s); $D_{down}$, $n = 10{,}592$ (m: 0.15 ± 0.05 s); $W_{up}$, $n = 11{,}207$ (m: 0.16 ± 0.06 s); $W_{down}$, $n = 11{,}399$ (m: 0.15 ± 0.05 s)

($F(1,8) = 5.22$, $p = 0.052$, $\eta p^2 = 0.39$), confirming that *OL* was constant between conditions.

## Discussion

We studied gaze behavior and its coordination with hand movements in a cyclic Fitts' task as we manipulated ID via *W* and *D* scaling. Scaling ID via *W* or *D* resulted in different gaze behaviors, and we observed (weak) signs of hysteresis. *W* vs. *D* scaling differences (mostly) disappeared, however, when gaze behavior was viewed as a function of MT rather than ID, supporting previous findings (Lazzari et al. 2009). In addition, the OL between hand and eye movements appeared to be constant and independent *of ID and MT*. In what follows, we will interpret the reported results in terms of the organization of eye–hand coordination and discuss the consequences for coordination theories and potential dynamical models. First, however, we need to point out that, in corroboration to previous observations (see Huys et al. 2015; Meyer et al. 1988; Sheridan 1979; Welford et al. 1969), we found that whether *ID* is scaled via *W* or *D* affected the $MT/ID_e$ relation. As these differences were not the main interest of our study, we will not further discuss them (for a review, see MacKenzie 1992). Regardless, these differences imply that dissimilarities between the *W* and *D* scaling in gaze behavior as a function of $ID_e$ might be confounded by differential effective task performance as differences in hand movement kinematics may be reflected in eye–hand coordination. The influence of *W* vs. *D* scaling

on the hand movements was moderate, however. In addition, our data suggest that MT rather than $ID_e$ determines eye–hand coordination (see below). Thus, we are confident that any potential confounding is limited and affects the conclusions drawn at most negligibly.

## Eye–hand synchronization is constrained by a minimal saccade time

The analysis of the *E/H* ratio showed similar results as those found by Lazzari et al. (2009), some differences between experimental conditions notwithstanding. For IDs above 2.9 and MTs above 0.250 s, participants made a saccade for every hand movement, resulting in an *E/H* ratio close to one. When movement times were shorter or $ID_e$ was lower, participants made fewer saccades than hand movements and the *E/H* ratio decreased.[2] In other words, for moderate to high ID values, accurate visual information was available during hand arrival at each target (see also Bootsma et al. 2002). For decreased ID (and shortened MT), the decreased *E/H* ratio suggests that immediate, high precision visual information was not needed to ensure arrival at each target. In these cases, intermittent monitoring was used where visual information could only verify task execution globally, perhaps aided by other sources of information such as proprioception. Apparently, (accurate) visual information is less essential for adequate task performance at low *ID*. Based on the decreased necessity for eye movements at low ID, Lazzari et al. proposed that the information used for the control of rhythmical aiming movements is divided into two modes: a visual based mode and a more proprioceptive mode. In the former, precise visual information is needed at each target arrival to ensure accurate movements, while in the latter visual feedback becomes less important and there is an increased use of mass-spring properties of the muscular system (Guiard 1993).

Lazzari et al. (2009) only manipulated the ID through changes in *W*. By scaling *ID* via either *W* or *D*, we showed a difference in *E/H* ratio between scaling conditions (see Fig. 3; Table 2 for the across participant and individual-based analysis, respectively). In both analyses, the critical *ID* where *E/H* ratio = 0.5 was lower when ID was changed through *D* than when it was changed through *W*. However, these differences disappeared when representing the *E/H* ratio as a function of *MT*. This could indicate that the differences in gaze behavior in relation to ID were simply a consequence of differences in effective performance. Yet, at

least one participant showed differences that cannot simply be explained by differences in effective performance. This participant did not achieve *E/H* ratios lower than 0.5 in the *D* conditions, but did so in the *W* conditions. Taken together, while these results are not unequivocal, they allow us to tentatively conclude that at least for some people, gaze behavior reacts differently to changes in *D* and in *W*.

Within the *W* and *D* conditions, we searched for hysteresis in eye–hand coordination. When presenting *E/H* ratio as a function of *ID*, hysteresis was only found in the *D* condition. Unlike the differences between *W* and *D* conditions in general, this effect cannot be easily explained by differences in effective performance, as hysteresis was observed neither in hand MT nor in MC. Then again, in keeping with the difference between the *W* and *D* conditions, the hysteresis mostly disappeared when presenting *E/H* ratio as a function of *MT*. Though the $D_{up}$ and $D_{down}$ conditions still differed from each other, the effect size was small and critical values in all conditions were comparable, differing by less than 0.01 s between conditions. In sum, the results showed some signs of hysteresis, but practically only when scaling *D* and presenting gaze behavior as a function of $ID_e$.

The differences between experimental conditions almost completely disappeared when eye–hand coordination was viewed as a function of hand MT rather than as a function of the $ID_e$. This supports Lazzari et al.'s (2009) hypothesis that eye–hand synchronization relates more directly to MT than to $ID_e$. In fact, differences between conditions not only disappeared, but *MT* also explained more of the variance in *E/H* ratio for all conditions than $ID_e$ did. This suggests that the effect of $ID_e$ on eye–hand coordination is indirect and that MT effectively constraints eye–hand coordination. In fact, $ID_e$ was not sufficient to predict the *E/H* ratio accurately without taking into account how ID was scaled and in which direction. In contrast, *MT* alone could be used to predict the *E/H* ratio. We thus tentatively conclude that eye–hand coordination depends more lawfully on MT than on $ID_e$. Our results are thus supportive of Lazzari et al.'s claim that saccade initiation is limited by systemic constraints and that the refractory period of the eye and a minimal dwell time needed for information pickup together determine whether a saccade is initiated.

As such, it is not surprising that no correlation was found between critical values for MC and critical values for *E/H* ratio. Indeed, there is little reason to believe that more continuous hand movement would go along with a shorter limit for saccades.

## Eye–hand latency is (approximately) independent of *ID* and *MT*

The possibility of a systemic limit does not explain the timing between hand and eye movements. Interestingly, the

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[2] Lazzari et al. (2009) report that for movement times lower than 350 ms, the E/H ratio decreases, but they do not report critical values where *E/H* ratio = 0.5 as we did here. Visual comparison of the data suggest that our results are similar to those reported by Lazzari and colleagues.

start and finish of the eye movements did not coincide with either hand peak acceleration or peak velocity, as repeatedly found for discrete movements (e.g., Binsted et al. 2001; Helsen et al. 1998). This demonstrates that even for high IDs, cyclical movements are not equivalent to a concatenation of 'from A to B' discrete movements (Huys et al. 2015). Rather than coinciding with specific hand movement events, OL remained fairly constant across all conditions and did not correlate with MT. Only few other studies have investigated the timing in eye–hand coordination in cyclical aiming tasks. The two studies (Lazzari et al. 2009; Terrier et al. 2011) known to us reported different (onset) latencies between hand and eye movements. Lazzari and colleagues used a Fitts' paradigm with constant target distance. They found that for MT greater than 550 ms, the eye had a relatively constant phase lag of $\pi/6$, i.e., the eye arrived at the target when the hand had spent approximately 18% of its movement time. For MT values between 350 and 550 ms, they found a shift towards $\pi/2$, and for MTs fewer than 350 ms the phase locking vanished (the relative phase spread over the whole $2\pi$ interval). Terrier and colleagues used a Fitts-like paradigm where participants tapped physical targets that were mounted on a screen in front of them. They found that the eyes left before the hand, as in discrete aiming and pointing tasks, with a decrease of the time between hand and eye departure with increasing ID. We can only speculate as to why our results differ from the above findings. First, the difference in head-constraints might have influenced the relative timing of hand and eye movements. In our study, the head was only immobilized by ordering participants to rest their head on a chinrest, whereas in Lazzari et al. participants had their head strapped so as to be immobile, and in Terrier et al. they were free to move their heads. Second, the tapping task in Terrier et al. provides different constraints on movement than the 'sliding' Fitts' task. Actually, tapping a target likely evokes discrete movements more so than sliding between targets. Last, differences in experimental setup and in acceleration and velocity thresholds for saccade detection might have slightly shifted start and endpoints when comparing our data with Lazzari et al.'s or Terrier et al.'s. Thus, it remains to be seen under what conditions OL is constant and on what variables it depends.

## Impact for theoretical models

How do the results of this study fit with existing theories of eye–hand coordination? Perhaps the most commonly used theory for goal-directed aiming is Woodworth's two-component model (Elliott et al. 2001; Woodworth 1899). Accordingly, movements consist of an initial impulse phase which accelerates the hand toward the target and a control phase in which visual information is used to bring the limb to rest on the target. Following this line of reasoning, the

decrease in eye-movements at low ID can be explained by the reduced need for visual feedback in the control phase. At the same time, however, the delineating of a ballistic impulse phase and a subsequent control phase is at odds with the nearly harmonic movement cycles at low ID. Regardless, the constant OL might be implemented in this conception as some sort of sensory delay or processing time that leads to a difference in the start of the hand and eye movements.

Because dynamical systems models have been able to explain most of the kinematics of a cyclic Fitts' task (Mottet and Bootsma 1999), it would be worthwhile to see if gaze behavior could be included in such a model. To capture the kinematics of eye–hand coordination in a dynamical model, it would be necessary to account for both the decrease in *E/H* ratio as well as the relatively constant *OL* in eye–hand coordination. What would be the outline of such a model? First of all, we deem it unlikely that saccadic eye movements are oscillatory (i.e., adhere to a limit cycle dynamics), as proposed by Lazzari et al. (2009). Rather, it is more probable that since saccadic eye movements make the gaze jump from one fixed location to another, the targets act as attractive fixed points. A bistable system adept for such jumping behavior was modelled by Jirsa and Kelso (2005). The corresponding system is excitable, which means that it has a separatrix (i.e., a structure that functions as a threshold) that divides the phase space between the two stable fixed points. To move from stable fixed point A to B, the separatrix (an unstable 'manifold' [point, line or surface in the phase space]) has to be crossed, which can be achieved via a brief, mathematically non-autonomous, impulse (see Huys et al. 2008). When coupled to an oscillator (the hand movement), either the non-autonomous impulse may be omitted if the coupling takes care of bringing the system across the separatrix or it may be coupled to the oscillator. What would such a coupling look like? Given that the OL is roughly constant, the onset phase will not be. Thus, a typical coupling such as the HKB one (Haken et al. 1985), where the phase lag between two oscillating systems is constant, can be expected to fail. Instead, it seems more likely that some sort of lag or delay is incorporated in the timing of the impulse. The exact nature of such a delay is open for discussion but a tentative explanation is in terms of a sensory delay in the control processes governing the movement and assuring the eye–hand movements coupling. Granted that the constant OL is adequately captured, a suitable system should also account for the decreased frequency of eye movements relative to the hand movements. The system as modelled by Jirsa and Kelso (2005) includes an overshoot and slow return phase after movement execution, which acts as a refractory period. Such a model system would then effectively limit the maximum frequency of the eye movements (see also Huys et al. 2008 for limits on movement frequency in an excitable mono-stable system). Additionally, the strength

of the coupling between hand and eye movements (or the amplitude of the impulse) could be related to the need for visual information to control the hand movements. At low ID, the impulse would not, or be less likely to, get the system past the threshold, leading to a decrease in *E/H* ratio. A full investigation of the possibilities and feasibilities of a dynamical model that includes gaze behavior awaits further theoretical (and empirical) research.

In conclusion, we found that the effects on eye–hand coordination can be dissociated and that some signs of hysteresis are present when *ID* is scaled via *W* or *D*. These differences disappeared when it was expressed as a function of MT rather than ID. Thus, eye–hand coordination appears to depend more lawfully on MT than on ID, and a minimal saccade time constrains eye–hand synchronization. Additionally, *OL*, the timing between the start of the hand and saccadic movements, was relatively constant and independent *of ID and MT*, suggesting that a constant delay should be implemented in a dynamical model of eye–hand coordination in rhythmic precision aiming.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicting interests.

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