[1]Gaze-Mouse Coordinated Movements and Dependency with Coordination Demands in Tracing

Shujie Deng[a], Jian Chang[a*], Julie A. Kirkby[b], Jian J. Zhang[a]

{sdeng, jchang, jkirkby, jzhang}@bournemouth.ac.uk

[a] National Centre for Computer Animation, Bournemouth University, Poole, United Kingdom [b] Psychology Department, Bournemouth University, Poole, United Kingdom

* Corresponding author

Abstract: Eye movements have been shown to lead hand movements in tracing tasks where subjects have to move their fingers along a predefined trace. The question remained, whether the leading relationship was similar when tracing with a pointing device, such as a mouse; more importantly, whether tasks that required more or less gaze-mouse coordination would introduce variation in this pattern of behaviour, in terms of both spatial and temporal leading of gaze position to mouse movement. A three-level gaze-mouse coordination demand paradigm was developed to address these questions. A substantial data set of 1350 trials was collected and analysed. The linear correlation of gaze-mouse movements, the statistical distribution of the lead time, as well as the lead distance between gaze and mouse cursor positions were all considered, and we proposed a new method to quantify lead time in gaze-mouse coordination. The results supported and extended previous empirical findings that gaze often led mouse movements. We found that the gaze-mouse coordination demands of the task were positively correlated to the gaze lead, both spatially and temporally. However, the mouse movements were synchronised with or led gaze in the simple straight line condition, which demanded the least gaze-mouse coordination.

Keywords: Human-Computer Interaction; eye-hand coordination; gaze-mouse coordination; coordination demands; mouse tracing; eye tracking

1. Introduction

Eye-hand coordination describes the coherent control of eye movements and hand movements with visual input as well as proprioception feedback. Studies have shown a typical coordination mechanism that eye movements lead hand movements, which has been applied in many gaze-modulated human computer interaction techniques such as MAGIC

---

[1] *This is an Accepted Manuscript of an article published by Taylor & Francis in Behaviour & Information Technology on 11th May 2016, available online:* **http://www.tandfonline.com/10.1080/0144929X.2016.1181209**

pointing (Zhai et al. 1999). In MAGIC pointing, the gaze is used to bring the mouse cursor next to the region of interest and fine adjustments are made using the hand. This type of technique is applicable to tasks such as point to point transitions, regardless of the transition path. When the transition path matters, such as tracing, it is interesting to apply similar gaze modulated techniques in these tasks. Tracing is as common as pointing and selecting tasks, for example, to digitise hand-drawn figures (Pfeuffer et al. 2015), but the underlying gaze-mouse coordination can be more complicated. Surprisingly, there have been few studies that have investigated the coordinated relationship between pointing devices and gaze in tracing tasks, in comparison to several studies that have studied tracing within eye-hand coordination. Although line tracing applications that integrate gaze and pointing devices already exist, such as the digital pen tracing application designed by Pfeuffer et al. (2015) which was developed by discretising the drawing line into segments, so the gaze-integrated manipulations were still point based, similar to other gaze-facilitated interactive techniques.

It is easy to assume that gaze always leads hand or mouse cursor but this is not absolute. Liebling and Dumais (2014) reported a study where the mouse cursor led gaze at times where the type of visual stimuli affected the leading or lagging between the two. This uncertainty may degrade the performance of applications that rely on the gaze lead. Imagine, in MAGIC pointing, the cursor warps to the gaze's vicinity when the hand is leading; the cursor is actually warping away from the region of interest. Therefore, for interactive techniques, designed with the premise of gaze leading, it is critical to distinguish whether gaze leads or the hand leads.

We were interested to see if gaze lead effects also occur during tracing with pointing devices and, further, to quantify these effects, both temporally and spatially. In addition, the differences of lead time and gaze-mouse patterns in previous studies have shown a possible underlying variance due to task complexity. Simple tasks require limited gaze-mouse coordination demands while complex tasks are more demanding. The coordination demands in the current paper are referred to as the perceptual complexity of the trace task. We, therefore, predicted that the degree to which the task required more or less gaze-mouse coordination demands would impact on the variance of gaze lead. Furthermore, the two would be positively correlated, that is, if the complexity of the task increased and gaze-mouse coordination demands increased, the lead time of gaze would increase. Therefore, we designed a task that required subjects to use the mouse cursor to pick up a sphere and move it along a trace under three conditions of complexity in a 2D virtual environment.

In summary, the aim of this study was twofold; first, to test the hypothesises that gaze-mouse coordination would yield comparable behavioural patterns as eye-hand coordination, in as much as gaze would typically lead mouse movement, and second, that the spatial and temporal lead effect would differ between conditions due to differences in gaze-mouse coordination demands. The findings serve as a preliminary foundation for future research on the factors that affect causality between gaze and mouse cursor positions, which can also provide a theoretical basis for further improvement of gaze-modulated input design.

The paper proceeds as follows. In Section 2, we present the literature background. In Section 3, we describe the experiment methods. Section 4 is dedicated to data analysis results and discussion of limitations and implications. Section 5 concludes the paper.

2. Background

Eye-hand coordination has been studied in various human behavioural tasks, including object reaching and pointing (Biguer et al. 1982; Neggers and Bekkering 2000; Ariff et al. 2002; Crawford et al. 2004; Masia et al. 2009), web browsing (Chen et al. 2001; Rodden et al. 2008; Guo and Agichtein 2010), goal-directed aiming (Binsted et al. 2001; Behan and Wilson 2008), visually guided tracking (Gauthier et al. 1988; Vercher and Gauthier 1992; Xia and

Barnes 1999; Tramper and Gielen 2011), drawing (Reina and Schwartz 2003; Gowen and Miall 2006; Coen-Cagli et al. 2009; Tchalenko and Chris Miall 2009), and trajectory tracing (Gowen and Miall 2006; Tramper and Gielen 2011). Other more complex tasks or applications that combine sequential movements have also attracted growing research interests, such as object manipulation (Johansson et al. 2001; Bowman et al. 2009) and virtual laparoscopic surgery (Yamaguchi et al. 2007). It has been verified in these tasks that there is a direct relationship between eye movements and hand movements. In virtual reality, kinematic movements of the hand were typically transited to reflect the movements of pointing devices, such as a mouse or a haptic stylus, which were virtualised to present the interaction between users and the virtual environment.

Previous research has focused on gaze-hand coordination (Biguer et al. 1982; Neggers and Bekkering 2000; Binsted et al. 2001; Johansson et al. 2001; Ariff et al. 2002; Reina and Schwartz 2003; Crawford et al. 2004; Gowen and Miall 2006; Coen-Cagli et al. 2009; Masia et al. 2009; Tchalenko and Chris Miall 2009; Tramper and Gielen 2011), studying user behaviour patterns where human computer interaction was not their primary concern. When a medium, such as pointing devices or haptic interfaces, is involved in human-computer interaction rather than direct use of physical hands, the users may behave differently from their natural habits in the interaction tasks. For instance, Wang and MacKenzie (1999) have found increasing orientation time for graphic-to-graphic matches and spatial errors for physical-to-graphic matches when haptic devices were involved.

Existing investigations into physical visuomotor tasks have revealed evidence of spatiotemporal leading of gaze position to hand movement with a high correlation between the two. Johansson et al. (2001) designed an object reach and grasp task, and found that gaze provided visual guidance for hand movement by marking the critical position where the fingers were reaching or targeting the object. In a curve drawing task, Reina and Schwartz

(2003) noted that gaze position clustered into several groups along the trajectory of the hand movement; they found that gaze remained still while the hand was approaching the object or moving away from it, then the gaze saccaded ahead of the hand position onto the next cluster. The fixation clusters tended to be located near high curvature areas along the hand trajectory, and the saccades occurred when tangential hand velocity reached a local minimum.

Various methods for quantifying the lead time have been developed based on the complexity of the tasks. In point-to-point tasks, goal-directed reaching, pointing, or tapping, these tasks normally require a single saccade or two. By calculating the difference in time between gaze on target and hand on target discretely, the lead time of gaze can be straightforwardly quantified. Ariff et al. (2002) designed a pointing task with unseen stimuli during hand movements on a horizontal plane. They reported that the saccades constantly occurred at the position where the hand needed an unbiased estimation of 196ms (on average) to catch up. It indicates that a saccade typically makes an estimation of the future position of the hand in point-to-point reaching tasks.

Continuous tasks such as tracing and tracking typically involve a sequence of saccades, where the leading effect of gaze cannot be simply defined by a single discrete saccade. Delay found by cross-correlation on each component (horizontal, vertical and depth direction) has been widely used as a benchmark method (Mrotek et al. 2006; Gielen et al. 2009; Tramper and Gielen 2011). This method normalises data by subtracting the statistical mean of the data and applies a Hann window before cross-correlation which helps to eliminate constant spatial noise. However, this method yields results in each component due to limits brought in by using cross-correlation. Typical values of gaze lead time found by this method are 23±38ms in azimuth, 42±28ms in elevation, and 266±175ms in depth for a tracking task; 220±125ms in azimuth, 230±125ms in elevation, and 390±180ms in depth for a tracing task (Gielen et al. 2009). Tramper and Gielen (2011) further analysed the total lead time calculated by cross-correlation by modelling it as the sum of saccadic lead time and primary lead time. This work updated the average time that gaze led the hand in tracking tasks of 28±6ms for the frontal plane, and 95±39ms for changes of vergence, and in tracing tasks, lead time of 287±13ms for the frontal plane and 151±36ms for changes in depth. It also demonstrated a constant spatial lead of gaze of about 2.6cm in 3D visuomotor transformations, which corresponded to about 2° in visual eccentricity.

Similarly, it has been proven that gaze and mouse cursor positions have a strong relationship in human-computer interaction tasks, with gaze leading mouse movements. Chen et al. (2001) have found in web browsing, 84% of the screen regions the mouse lingered were also visited by gaze; further, there was over a 75% chance that a mouse would move to a meaningful region that was very close to the gaze. This suggested that a mouse cursor could be an alternation to show regions of interest in web browsing. Moreover, active mouse movement patterns have been explained in browsing web search pages, which tended to follow the gaze position vertically, as well as marking a particular region of interest (Rodden et al. 2008). A preliminary study has been undertaken for predicting gaze positions by analysing mouse cursor positions based on a combination of findings from previous studies in web searching (Guo and Agichtein 2010).

However, apart from the typical pattern that gaze leads mouse, additional patterns have also been reported. Smith et al. (2000) examined two simple target pointing tasks that required subjects to select two fixed targets alternately, and to select a target presented at random locations. They found there existed several different gaze-mouse coordination patterns that gaze not only led the mouse cursor but also directly followed the cursor, or switched between target and cursor. Bieg et al. (2010) studied three target search and selection tasks where the subjects were asked to find a single target, or a known target from a grid of targets, or an unknown target from a pile of randomly scattered targets. They found that when the target was unknown, the subjects consistently followed their gaze with the mouse cursor rather than the other way around. Liebling and Dumais (2014) further inspected gaze-mouse coordination using a variety of target types and applications. They reported that the gaze led the mouse only about two-thirds of the time, and the leading or lagging effect of the gaze depended on the type of target and familiarity with the application. However, the cause remains unclear.

3. Methods

3.1. Participants

Fifteen subjects (11 males and 4 females, age 28.5±1.8 (Mean ± SE) years) volunteered in the experiments. None of the participants had any motor or neurological abnormalities. The subjects reported they had either adequate natural visual acuity or corrected vision with glasses. All subjects reported to be right-handed and fluent with computer/mouse operations. All the experiments were conducted following the principles of the Declaration of Helsinki and Bournemouth University's research ethics policy, and were approved by the Research Ethics Committee Panel at the Media School, Bournemouth University. Written consent was obtained from each subject after explanation of the experiment.

3.2. Apparatus

A desktop mount eye tracker EyeLink 1000 of SR Research was set up to record gaze movement with sampling rate at 1000Hz. The spatial resolution was 0.01° and the average accuracy was 0.25° - 0.5°. The desktop mount used a chin rest to minimise head movement. Although viewing was binocular, only the right gaze movements were recorded. Subjects sat 66cm away from the display screen which was a 20" Formac ProNitron 21/750 monitor with a frame rate set to 120Hz. A mouse with a sampling rate of 120Hz and a keyboard was provided for interaction within the experiment. All position data were recorded with respect to the pixel coordinates whose origin was set at the upper left corner of the screen.

3.3. Stimuli

The tailored task was programmed with C++ and OpenGL. The task scene was presented with a black background containing a small sphere with a diameter of 1.56°, a bordered square box with a side length of 5.64° and a border width of 0.1°, and a predefined trace with a width of 0.17°. The trace was generated by random hand drawing, and there were three conditions of different complexity levels that required low to high gaze-mouse coordination demands (see Figure 1 a-c):

- Low gaze-mouse coordination demands (LD): a simple straight line, with a length of 24.70°, no curves, and direction of 33.75° upwards from the horizontal line.
- Moderate gaze-mouse coordination demands (MD): a simple curve, with a length of 42.70° and two curves.
- High gaze-mouse coordination demands (HD): a complex curve, with a length of 94.14° and fourteen curves.

The displays within each trial of the same condition were identical to those shown in Figure 1 a-c. The box was fixed at the upper left screen as the destination of the trace. The trace started from the lower right screen and ended at the box. Subjects needed to use a mouse to move the sphere from the starting end of the trace, and traverse it along the trace until it got into the box.

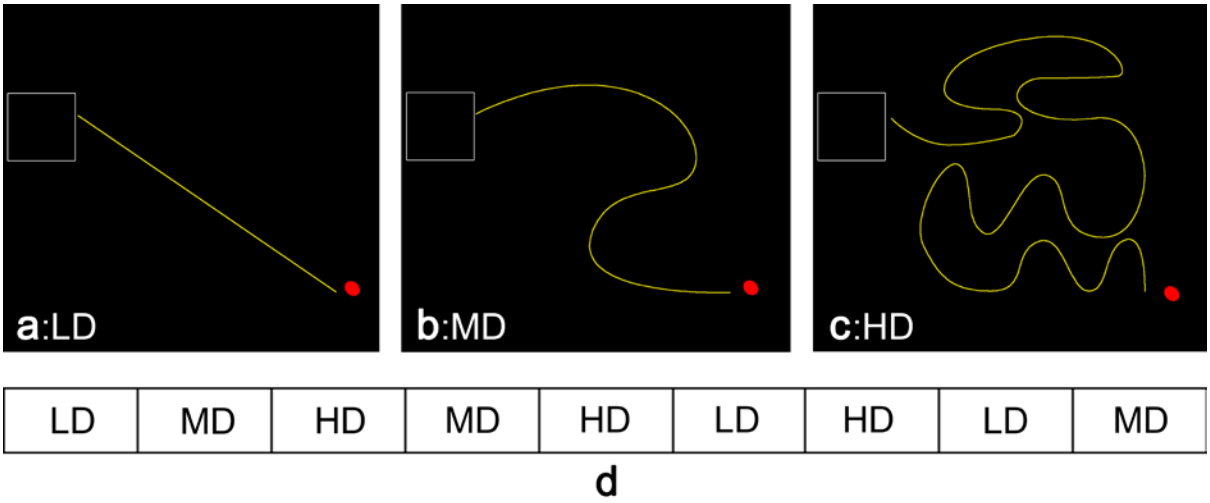

Figure 1. Stimuli for (a) LD the straight line, (b) MD the simple curve, and (c) HD the complex curve. (d) is the order of trial conditions in each trial set.

3.4. Procedure

There were nine trials in one trial set. Each condition appeared once in every group of three. The order of the trials was balanced to prevent the chance that the same trace showed up continuously. All data were recorded in the same order for every trial set as demonstrated in Figure 1d. Note that we did not use randomisation to balance the order because a randomisation among the nine trials may cause the same conditions showing up in a row; a randomisation within each group of three may result in the situation that the last condition of the previous group is the same as the first condition of the next group.

Before each trial started, the screen was blank of background colour with only a little white cross in the middle. To eliminate bias introduced by the initial state, all subjects were asked to fix their gaze on the cross before moving onto each trial display. At the beginning of a trial, the sphere appeared at a random position on the screen. When the sphere was picked up, its colour changed to highlight the picked-up status. A trial ended when the subject released the sphere in the target box after following along the trace. Before data recording, each subject carried out one pre-trial of each condition to familiarise themselves with the experiment procedure. Ten trial sets were recorded for each subject. During recording, if the subject veered off the trace, this trial would be discarded and the subject needed to redo it.

3.4.1. Calibration

Right eye calibrations were performed binocularly (e.g. during calibration participants viewed the stimuli with both the right and left eyes). The horizontal calibration range was 29.45°, vertical calibration range was 21.05°. During calibration, the subject was instructed to stare at one of the nine point grid pattern fixation points. In this process, the initial fixation position was accepted by the experimenter when the pupil appeared stable; the remaining fixation positions were automatically recorded by the calibration system when a stable fixation was detected. The validation procedure was essentially identical to the initial calibration, and on the basis of the initial calibration and validation the discrepancy between these two data sets was computed. The calibration fixation points extended 0.6°, and a mean error of < 0.7° was accepted as an accurate calibration, and recalibration was performed if the validation error was > 0.7°. These calibration and validation procedures are standard. The experimental stimuli were presented when a successful calibration was completed. Following nine trials during the experiment, the calibration accuracy was verified, and at that point, recalibration was carried out if necessary. The mean ± SD of validation errors for all trial sets was 0.47 ± 0.14 degrees.

3.5. Data pre-processing

There were 1350 trials of 150 sets recorded in total (15 participants, each did 10 trial sets and nine trials in each trial set). By generally reading the trajectories visualised from the data, 9 trials were eliminated from the data processing because of calibration and recording issues, which means 99.3% of the trials were successfully completed. Due to order effect that might be introduced into the data, the first three trials of each trial set were removed from the analysis.

All data were stored on a hard disk for offline analysis with MATLAB (MathWorks). Each trial generated a data file and a screen recording video of the experiment process. The file recorded gaze positions on the screen at 1 kHz, along with start and end time of gaze movement events including fixations, saccades, and blinks. Mouse cursor positions and relative events were also recorded at 120Hz with timestamps. For each trial, the start time was defined as when the target sphere was moved to the start position of the trace, and the end time was defined as when the sphere was moved into the destination box. Mouse movement data were interpolated linearly to match with the frequency of gaze movement data for computational convenience. A Savitzky-Golay filter (Savitzky and Golay 1964) (span = 2% of the total number of data points per trial, degree = 2) was applied for both gaze data and mouse data to remove drifts introduced by blinks and trembles.

3.6. Analysis

3.6.1. Distance between gaze and mouse cursor

After pre-processing, a data matrix was generated for each trial. Each row represented one sample containing the following parameters: timestamp (*t*), gaze position *x* (*gpx*), gaze position *y* (*gpy*), mouse cursor position *x* (*mpx*), and mouse cursor position *y* (*mpy*). The Euclidian distance between gaze and mouse cursor positions on the screen (*DGM*) for the i^{th} sample row of a certain time *t* could be calculated by Eq. (1):

$$DGM_i = \sqrt{(gpx_i - mpx_i)^2 + (gpy_i - mpy_i)^2} \quad (1)$$

The *DGM* was calculated in pixels then converted to degrees of visual angle.

3.6.2. Lead time of gaze relative to mouse cursor

The projection of a gaze position on instantaneous mouse cursor moving direction for a certain gaze-mouse position pair is shown in Figure 2. The instantaneous lead time relative to the mouse movement could be defined by Eq. (2) where the velocity of the mouse cursor (v_m) was obtained by the central differencing scheme as shown in Eq. (3). Δt is the sampling interval, typically 1ms. During a fixation, the mouse cursor position would catch up with the gaze position, i.e., the displacement between gaze and mouse cursor (d_{gm}) shortens. Note that *DGM* is the norm of d_{gm}. Suppose v_m is uniform, t_{lead} will become smaller when d_{gm} shortens according to Eq. (2). In this case, at the time when a fixation started, t_{lead} had its maximum effect. Hence, only samples at the start point of fixations were examined for providing maximum leading availability.

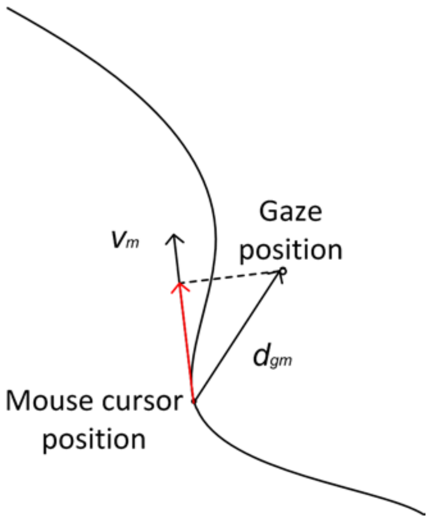

Figure 2. Illustration of all metrics needed for lead time calculation.

$$t_{lead} = \frac{\vec{d}_{gm} \cdot \vec{v}_m}{\left\| \vec{v}_m \right\|^2} \tag{2}$$

$$\vec{v}_m = \left(\frac{x(t+\Delta t) - x(t-\Delta t)}{2\Delta t}, \frac{y(t+\Delta t) - y(t-\Delta t)}{2\Delta t}\right) \tag{3}$$

3.6.3. Linear regression

To test dependency of gaze position and mouse cursor position, linear regression was applied on the *x*- and *y*-component of the gaze-mouse position pairs.

The coefficients of the fitted lines have been obtained for each qualified trial, as shown in Eq. (4) and Eq. (5), where *gpx* is gaze position *x*, *gpy* is gaze position *y*, *mpx* is mouse cursor position *x*, and *mpy* is mouse cursor position *y*.

$$gpx = k_x \cdot mpx + b_x \tag{4}$$

$$gpy = k_y \cdot mpy + b_y \tag{5}$$

In both equations, *k* is the slope of the fitted line and *b* is the intercept. Physically, *k* indicates the overall rate of change between gaze trajectory and mouse cursor trajectory. We define *k* as the tracing gain, which is the ratio of the length of gaze trajectory to mouse cursor trajectory. The other parameter *b* shows the average leading or delay distance.

When k>1, gaze position changes faster than mouse cursor movement; it tends to overshoot while mouse cursor traverses the same amount of distance, and the overall length of gaze's trajectory is longer than mouse cursor's trajectory; when k<1, gaze position changes slower than mouse cursor movement; it tends not to cover as much distance as the mouse cursor covers, and the overall length of gaze's trajectory is shorter than mouse cursor's trajectory; when k=1, the overall length of the trajectories of gaze and mouse cursor should be the same. When b>0, gaze leads mouse movement; when b<0, mouse leads gaze; when b=0, the movements of gaze and mouse are synchronised. A typical case is that k=1 and b>0, where gaze position and mouse cursor position can be superimposed with gaze leading.

Prior to applying linear regression, the data were normalised; this was due to the fact that the lead/delay relationship was highly related to the trace traversing direction. Here we consider the mouse cursor moving direction always conforms to the trace traversing direction. For example, in Figure 3a, when the *x*-component of the trace/mouse movement v_x goes in the positive direction of the *x*-axis, if gaze is leading, the coordinate of the gaze will be larger than the coordinate of the mouse cursor (*gpx* > *mpx*). However, when the *x*-component of the trace/mouse movement v_x goes in the negative direction of the *x*-axis (as shown in Figure 3b), the coordinate of the gaze will be smaller than the coordinate of the mouse cursor if gaze is leading (*gpx* < *mpx*). If data of the first scenario as in Figure 3a are fed into the linear fitting, parameter *b* will remain positive; data of the second scenario as in Figure 3b will cause *b* to decrease instead. In this case, the lead/delay effect will be neutralised, leading to the failure of showing reliable results. It is similar for the *y*-component with respect to the *y*-axis.

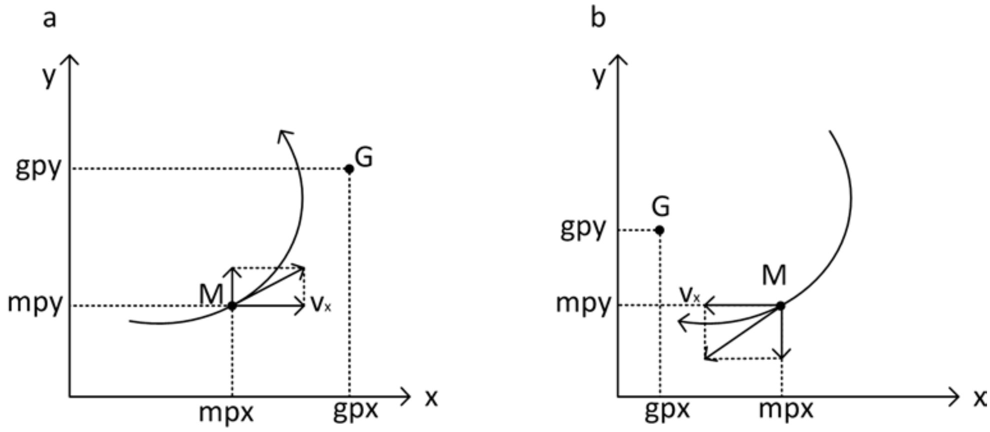

Figure 3. Example scenarios when (a) the gaze *G* is leading the mouse *M* movement and the *x*-component of the mouse movement conforms to the positive direction of the *x*-axis; (b) the gaze *G* is leading the mouse *M* movement and the *x*-component of the mouse movement conforms to the negative direction of the *x*-axis.

Therefore, to normalise the data, we used the axis directions as the reference; if the *x*-component (or *y*-component) of the current tracing/mouse direction conformed to the direction of the *x*-axis (or *y*-axis), the signs of both the gaze and mouse cursor *x*-coordinates (or *y*-coordinates) remained the same on the *x*-component (or *y*-component); otherwise, both signs were turned to the opposite.

3.6.4. Statistics

To test our initial hypothesis, which was whether there was a significant linear relationship between gaze and mouse movements, a *t*-test (Paulson 2010) on the regression slope was applied on all sets of coefficients fitted. To test our second hypothesis of whether the level of gaze-mouse coordination demands impacted differentially on any relationship between gaze and mouse movements, a one-way ANOVA was applied for each coefficient, k_x, b_x, k_y, and b_y, yielded from the linear regression, lead time t_{lead}, and gaze-mouse distance *DGM*. *Post hoc* Bonferroni tests were used to establish differences among the three conditions with different gaze-mouse coordination demands.

4. Results and discussion

4.1. Overall gaze-mouse behaviour in tracing

The overall performance of most subjects reflected the typical staircase-like gaze movement pattern (Type I) where the gaze position changed rapidly (saccades) then waited (fixations), forming an obvious staircase-like pattern in the plot of *x* or *y* coordinates with respect to time. Figure 4 shows a typical sample trial of Type I by presenting gaze movement (green solid line), fixation (blue circle), and mouse movement (red dashed line) for each condition: low level of gaze-mouse coordination demand (top row), moderate level of gaze-mouse coordination demand (middle row), and high level of gaze-mouse coordination demand (bottom row) in the frontal plane (left column), *x*-component (middle column), and *y*-component (right column) relative to time, respectively. Another type (Type II) of a smoother gaze movement pattern was observed to occasionally happen in two subjects' performance (see Figure 5). The time series of gaze movement (middle and right column) did not form the typical staircase-like pattern but continuously followed the stimulus trace more smoothly, where saccades and fixations were not significantly different in the plot. The fixations marked by blue circles are determined by the eye tracker software, where approximately equal counts of saccades were detected for both types in the same condition.

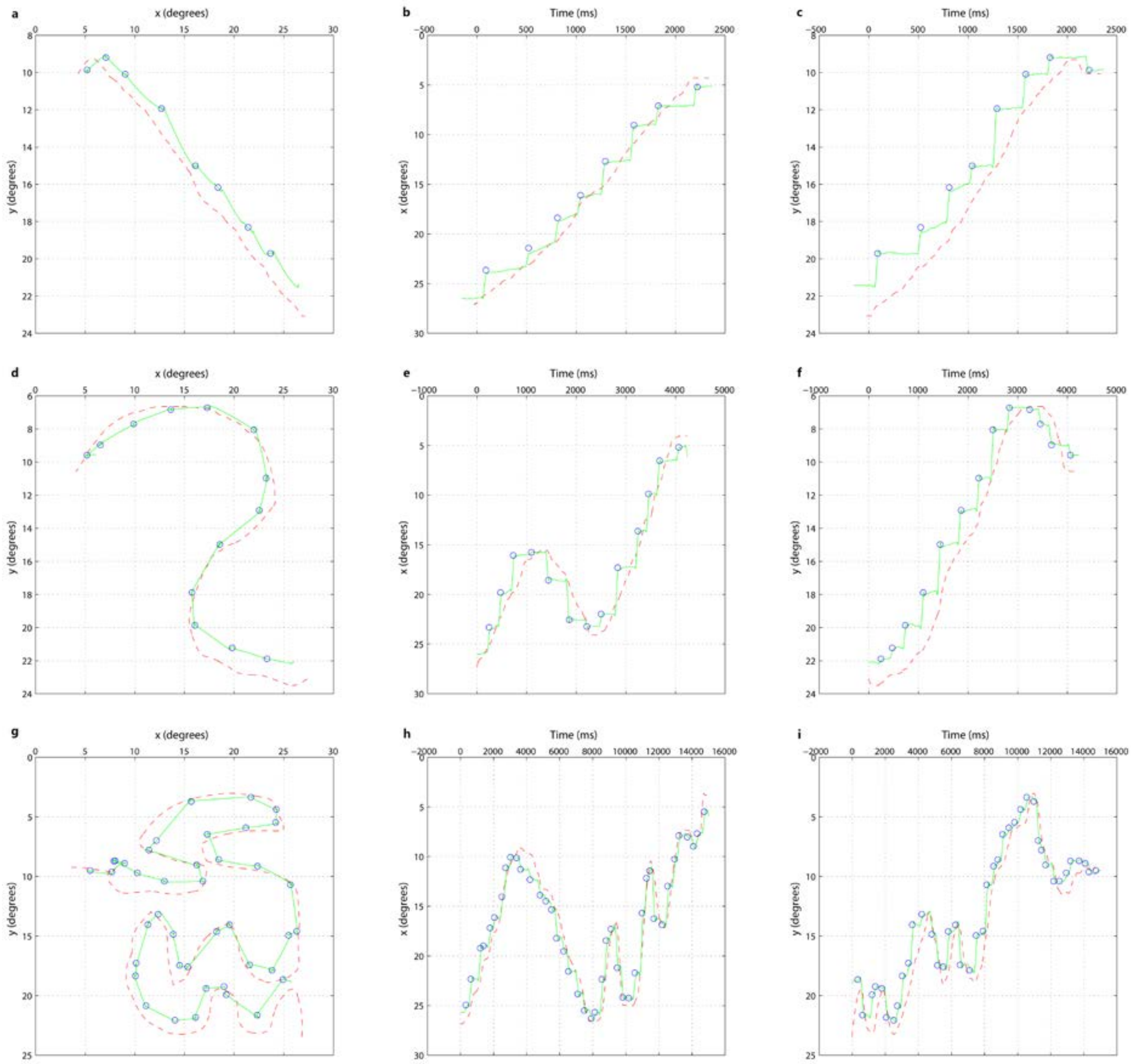

Figure 4. Type I gaze (green solid line) and mouse cursor (red dashed line) trajectories during tracing in low level of gaze-mouse coordination demand (top row), moderate level of gaze-mouse coordination demand (middle row), and high level of gaze-mouse coordination demand (bottom row). The left column shows the gaze trajectory and the mouse cursor trajectory in the frontal plane, the middle column and the right column show the corresponding time series for the *x*- and *y*-directions, respectively. Blue circles show the mean position where fixation occurred.

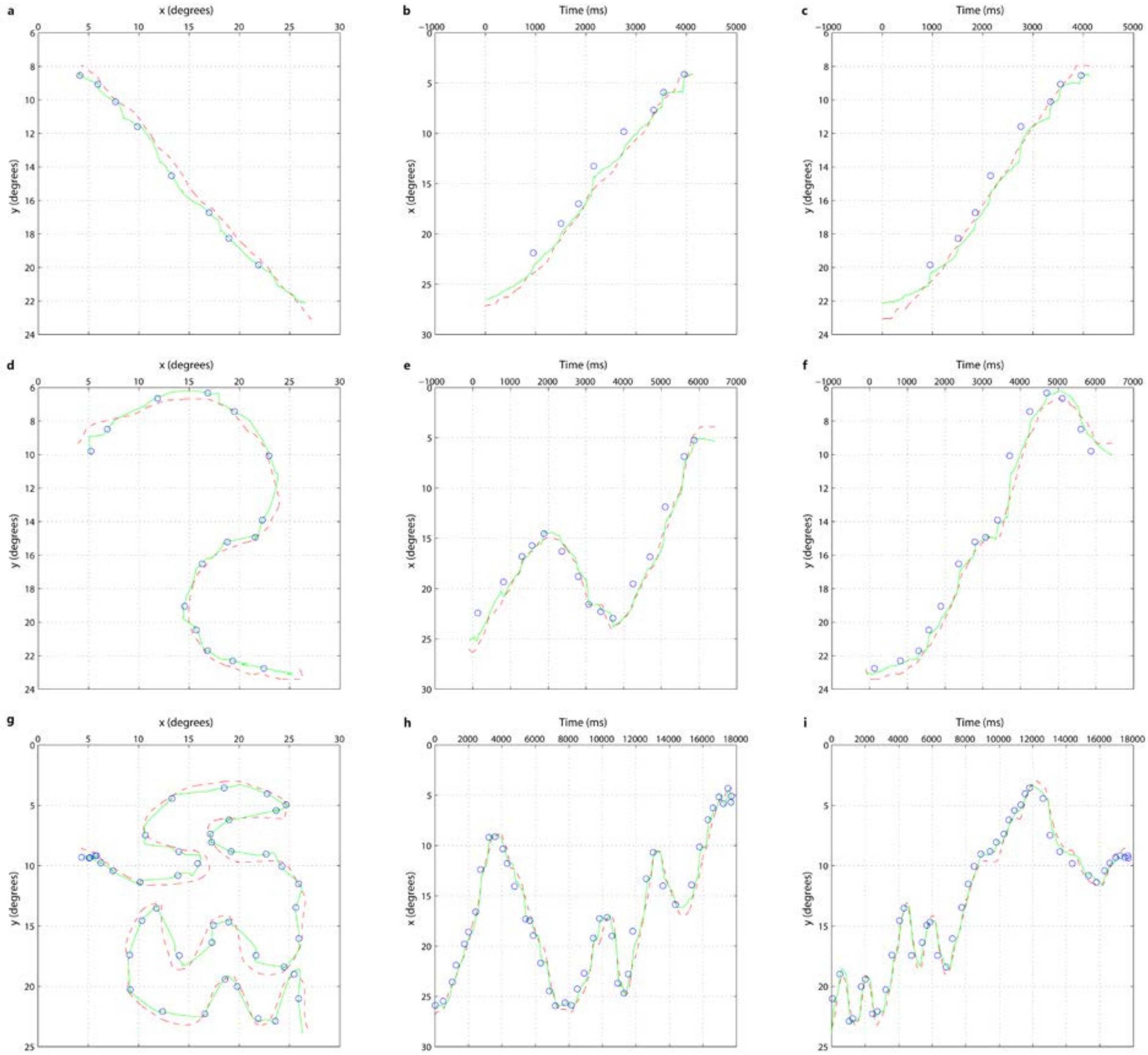

Figure 5. Type II gaze (green solid line) and mouse cursor (red dashed line) trajectories during tracing in low level of gaze-mouse coordination demand (top row), moderate level of gaze-mouse coordination demand (middle row), and high level of gaze-mouse coordination demand (bottom row). The left column shows the gaze trajectory and the mouse cursor trajectory in the frontal plane, the middle column and the right column show the corresponding time series for the *x*- and *y*-directions, respectively. Blue circles show the mean position where fixation occurred.

There is a possibility that Type II gaze movement was a combination of smooth pursuit and saccadic movement. Smooth pursuit usually occurs when the eyes closely follow a moving object (de Xivry and Lefevre 2007). Research has demonstrated that except for trained subjects (Purves et al. 2001), humans are not capable of smooth pursuit without a visible moving target. In this study, the moving object was the mouse-manipulated sphere.

Knowing that the subjects were not specially trained for that purpose, it suggested that the subjects' eyes were more closely following the movement of the sphere. However, when the Type II gaze movements were observed, the gaze was not directly following the movement of the sphere but leading it with an extremely limited amount of distance. Therefore, the Type II movements could be due to the predictable movements of the target, the visible trace, and the self-manipulated hand movements. In fact, atypical patterns of saccades were also identified in the data. Specifically, when a fixation occurs following a saccade, instead of staying relatively still, the gaze keeps moving forward with a velocity that is slower and smoother than the saccade. This may explain why in Type II gaze still leads but by a very limited amount. However, it was not the dominant pattern of gaze behaviour observed in the data; so further discussion of the Type II gaze movement is beyond the scope of this study.

4.2. Correlation in gaze-mouse coordination

4.2.1. Linear dependency

It is shown in the results that gaze and mouse movements are highly correlated in terms of position. To avoid the influence of the trace shape, linear fitting of the coordinates which is described in the section *Linear regression* was applied to provide a statistical mean of the gaze-mouse coupling of the x-component and the y-component, respectively. By analysing the t-score of the slope fitted from the linear regression and its corresponding p-value ($p < .001$) yielded from the t-distribution, it verified a spatial linear relationship of gaze-mouse coordination.

Table 1 shows the mean and standard deviation (SD) of the coefficients of linear regression that were either generated from all trials or from each condition. The tests on the regression slope using t-statistics for the x- and y-components both indicated that there was a significant linear relationship between gaze and mouse movements at the significance level of

5%. Columns R_x^2 and R_y^2 show the goodness of fit using the residual variance from the fitted coefficients. An R^2 with a value close to 1 indicates a good fit.

Table 1. Mean (SD) results of linear regression coefficients for each condition and for all trials.

Conditions	$\boldsymbol{k_x}$	$\boldsymbol{b_x}$ (deg.)	$\boldsymbol{R_x^2}$	$\boldsymbol{k_y}$	$\boldsymbol{b_y}$ (deg.)	$\boldsymbol{R_y^2}$
LD	0.99 (0.10)	-0.86 (1.34)	0.97 (0.04)	0.90 (0.14)	0.14 (0.47)	0.98 (0.03)
MD	1.05 (0.07)	0.42 (0.59)	0.99 (0.01)	0.88 (0.13)	0.19 (0.36)	0.99 (0.01)
HD	1.05 (0.07)	0.60 (0.38)	0.99 (<0.01)	0.90 (0.12)	0.33 (0.34)	0.99 (0.01)
Overall	1.03 (0.09)	0.06 (1.09)	0.98 (0.02)	0.89 (0.13)	0.22 (0.40)	0.99 (0.02)

The overall k_x shows that in the horizontal direction gaze traverses about the same distance that mouse cursor traverses. However, in the vertical direction, gaze traverses about 10% less than the distance that the mouse cursor does. The difference between k_x and k_y suggests that the vertical tracing gain is smaller than the horizontal tracing gain. The directional asymmetry of gaze movement has previously been reported in smooth pursuit where horizontal movements were more accurate and faster than vertical movements (Rottach et al. 1996). Our pattern of results suggests the possibility that such asymmetry also exists in saccadic eye movement.

The low gaze-mouse coordination demands condition shows significance on k_x (both *post hoc* Bonferroni tests with MD and HD showed $p < .001$). The results indicate that in the horizontal direction, the gaze covers slightly less distance than the mouse cursor when tracing with low gaze-mouse coordination demands; but when tracing with moderate to high gaze-mouse coordination demands, the gaze tends to cover slightly more distance. No significance has been observed on k_y for the three conditions ($F(2, 891) = 0.65$, $p = .52$), which indicates that the level of gaze-mouse coordination demands does not affect the tracing gain (k) in the vertical direction.

The results of b_x and b_y show that the gaze lead in both directions grows when gaze-mouse coordination demands increase (b_x: $F(2, 891) = 248.87$, $p < .001$; b_y: $F(2, 891) = 18.67$,

p < .001). Surprisingly, the b_x value under the low gaze-mouse coordination demands condition is negative, indicating that the mouse leads the gaze. This suggests that when the task demands less gaze-mouse coordination, the mouse cursor can follow the gaze very closely, which is reflected in the small gaze lead in the vertical direction; or even lead gaze instead, as shown in the horizontal direction. This pattern of results is in line with and extends previous studies (Bieg et al. 2010; Liebling and Dumais 2014). Due to the simplicity of the straight line that requires low gaze-mouse coordination demands, it may be possible that hand motion can be planned at the same time as the trace is initially seen, so proprioception can play the main role in guiding movements of the hand with visual feedback only acting as an accuracy validator. When vision provides the main guiding information for hand movements, i.e. under moderate and high gaze-mouse coordination demands, it mostly relies on an eye-brain-hand interaction. Under low gaze-mouse coordination demands, it seems to be a reversely hand-brain-eye interaction. This interplay can be essential in straightforward tasks or trained tasks when memory, other than real-time vision, stimulates the hand movement.

During tasks that required moderate to high gaze-mouse coordination demands, b_x is larger than b_y. It is assumed that the difference is caused by the shape of the trace. A supplement test was conducted to testify this assumption. We turned the stimuli traces 90° so that the horizontal and vertical movements were swapped. This supplement test data reflected that swap, in which b_y became greater than b_x, but k_x and k_y still remained the same. Therefore, this indicates that b is related to trace shape but not k. In this case, we cannot conclude a general leading distance (b) because the trace shape affects its x and y components, but it gives a hint of the possible shape coefficient defined by the proportions of horizontal and vertical traces, for determining the leading distance on each directional component x and y. According to the fact that all three k values for each condition are similar on each directional component, the tracing gain (k) is not significantly impacted by the trace shape, indicating that other untested trace shapes will share the same result in the same experimental setting.

The standard deviation of the low gaze-mouse coordination demands condition is larger than the other two for all four coefficients. This was caused by the too small number of saccades in some trials of this condition, which was unable to provide enough training data for the linear regression and then led to difficulties in obtaining more robust results.

4.2.2. Correlation between gaze speed and gaze-mouse distance

Figure 6a shows a typical case of the corresponding relationship between the gaze speed (green solid line), the speed of the mouse movement (red dashed line), and the gaze-mouse distance (blue dash-dot line) during a moderate gaze-mouse coordination demanding trial. The peaks of the green solid line represent the saccades; in between the saccades are fixations. Each saccade has one shorter peak on both sides; in other words, at the beginning and at the end of a saccade, there is a small acceleration of the gaze movement (see Figure 6b). Figure 6c gives a close-up of a single saccade. The backshoot at the right-hand side of the saccade, which is marked with a red circle, and the dynamic overshoot at the left-hand side of the saccade, which is also marked with a red circle, are clearly seen. The backshoot can be reflected by the first peak of speed in Figure 6b, and the dynamic overshoot can be reflected by the third peak of speed in Figure 6b. The overshoot could be evidently identified in the moderate and high gaze-mouse coordination demands conditions of every subject's performance except for some trials of the low gaze-mouse coordination demands condition and those who have Type II gaze movements. The dynamic overshoot is usually a correction since the target of the initial saccade is not perfect (Kapoula and Robinson 1986). Most studies discussed dynamic overshoots but backshoots prior to the initiation of a saccade are rarely mentioned in the previous literature. Deubel and Bridgeman (1995) reported much smaller backshoots than overshoots but in our specific tracing task, the backshoots are as evident as or only slightly smaller than the dynamic overshoots.

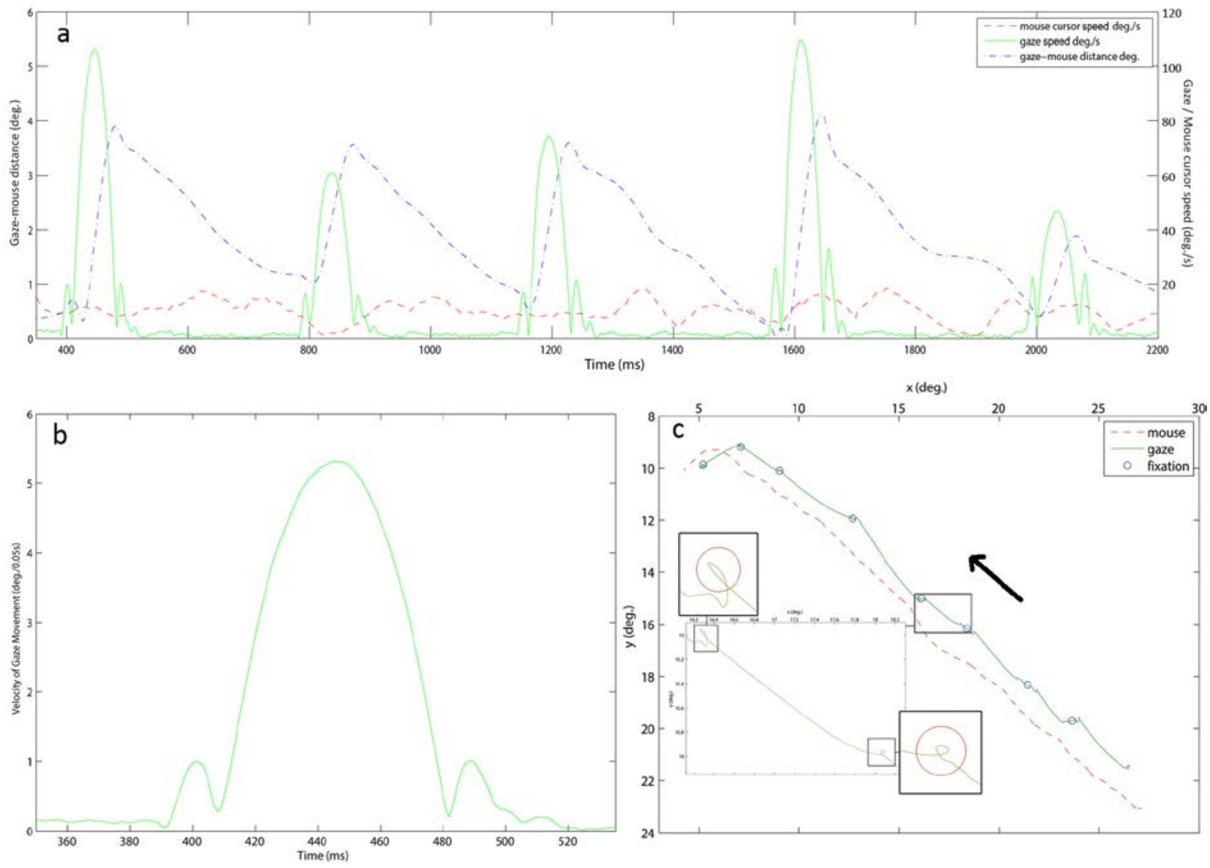

Figure 6. A sample of the relationship between gaze speed, mouse cursor speed, and gaze-mouse distance.

The number of peaks in the blue dashed-dotted line is consistent with the number of saccades. It shows the positive correlation between the gaze-mouse distance and the speed of gaze movement in mouse tracing. It is apparent that the gaze-mouse distance reaches its local maximum at the end of one saccade and its local minimum at the beginning of the saccade, suggesting that the mouse cursor is generally catching up with the gaze position.

4.3. Lead time in gaze-mouse coordination

We have validated the gaze lead effect in the discussion of *Linear dependency*. In this section, a direct evaluation of the lead time for each condition is provided. Table 2 gives the lead time obtained by the method explained in Eq. (2) for each condition. The positive values represent the gaze leading the mouse cursor. The significance test shows smaller average lead time on the low gaze-mouse coordination demands condition (both *post hoc* Bonferroni tests with MD and HD showed $p < .001$). It can be explained by two factors. One is that the velocity of straight line tracing is greater than that of curve tracing. Another is that in some straight line tracing cases the mouse cursor was leading in the horizontal direction but lagging in the vertical direction. This method integrates separate leading/lagging effects in the horizontal and vertical directions to one instantaneous mouse moving direction; so the results are neutralised by the lagging in the horizontal direction. Both factors can be testified in the current data. However, it is unclear to what extent each factor has impacted on the pattern of results. The lead time for moderate to high gaze-mouse coordination demands conditions is in agreement with the work of Gielen et al. (2009), indicating that the response time in the central nervous system during finger tracing is similar to mouse tracing.

Table 2. Mean ± SD results of lead time calculated by Eq. (2) and *DGM* for each condition.

Conditions	**LD**	**MD**	**HD**
Lead time (ms)	223 ± 154	283 ± 113	295 ± 87
DGM (deg.)	2.95 ± 2.08	2.95 ± 1.95	2.97 ± 1.91

Figure 7 provides an overview of lead time of all subjects across all conditions. It is noticeable that some subjects have very small lead time in the low gaze-mouse coordination demands condition. The minimum values represented by the bottom of the whiskers are even minus for these subjects. It is in accordance with the negative b_x that has been explained in the *Linear dependency* section. Because the lead time is only calculated based on the samples at the end of each saccade where the distance is supposed to be the maximum during each saccade and atypical saccadic movements still occur in Type II, the result of Type II still shows typical lead time.

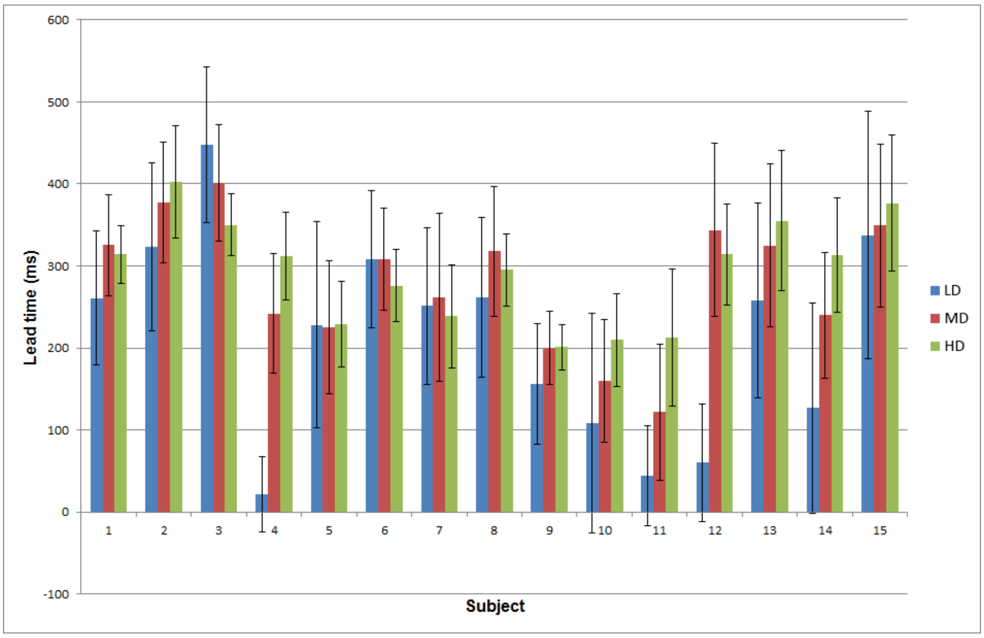

Figure 7. Average lead time for each subject grouped by different conditions.

4.4. Distance between the gaze and the mouse cursor during tracing

Figure 8 shows the distribution of the sampled distance of all gaze and mouse cursor position pairs. The mean ± SD of *DGM* is 2.96 ± 1.94 degrees for all sampled distances between gaze and mouse cursor position pairs, containing 72.04% of the samples. The mean (2.77°) is slightly larger but close to the lead distance of gaze found in Tramper and Gielen's work (2011), which was ~2°. The percentage of *DGM* that falls inside the 10° range is 99.36%, which agrees with the findings presented in studies of Binsted et al. (2001) and Bowman et al. (2009). This reflected the observation that the mouse cursor was coupling with gaze by keeping a distance within the high visual acuity area of the retina (which will be explained in the next paragraph). It is worth noting that Type II data showed very small mean *DGM* that was ~1° because smooth pursuit eye movements keep gaze-mouse distance to the minimum while Type I mainly distributed between [2, 3] degrees. The fit of samples only at the beginning of each fixation yields the mean ± SD of *DGM* to be 3.49 ± 2.22 degrees. Gaze-mouse distance for each condition is given in Table 2 which shows no significant difference for the three levels of gaze-mouse coordination demands ($F(2, 891) = 0.76$, $p = .47$).

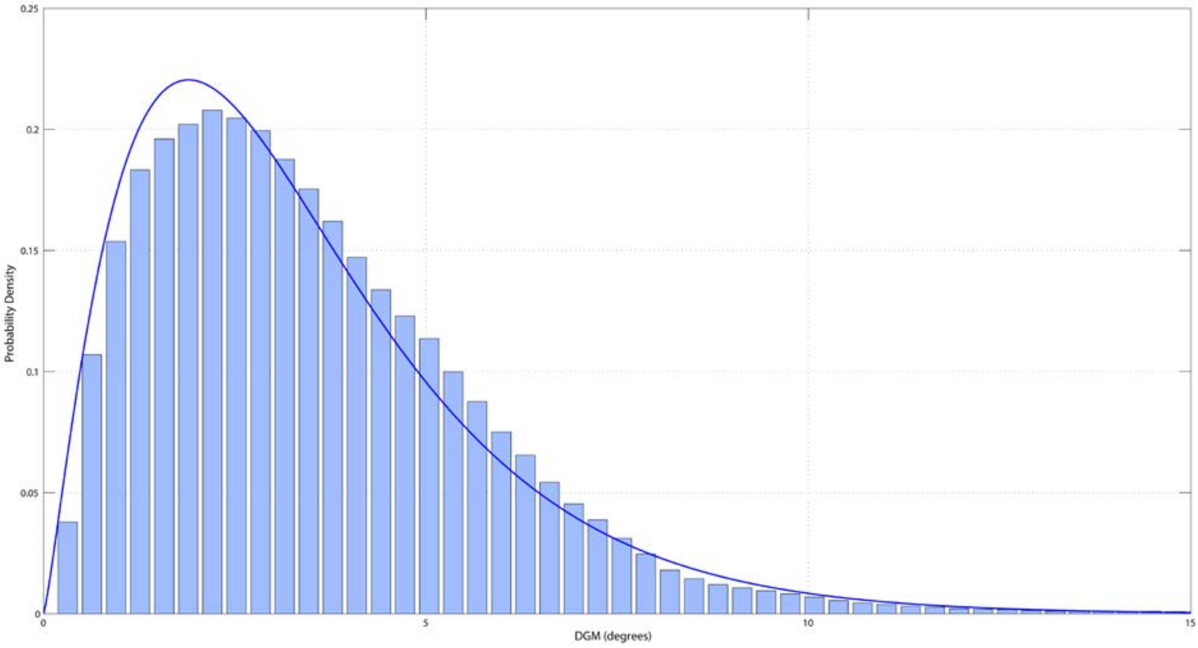

Figure 8. Distribution of *DGM* of data from all subjects and all conditions.

It is noticeable that the high spatial correlation between gaze trajectory and mouse trajectory does not perfectly guarantee superimposition of the two. For specific tasks like pointing to a specific position, a perfect overlap is possible (Neggers and Bekkering 2000). Previous work built the gaze lead model with the assumption that gaze and hand movements were perfectly superimposed (Tramper and Gielen 2011). However, in tasks like tracing, because it is a dynamic process, it is easier to introduce noise that affects the superimposition of gaze trajectory and trace stimuli, such as complexity of the trace, motor instability, attention shifts, distraction, the size of the motor tool, calibration noise, and personal habits amongst other factors. Our results suggest that the difference is related to the range of visual acuity area. It is well known that human vision achieves the highest acuity at the fovea which extends about 2° around the centre of the retina (Duchowski 2007). The region that circumscribes the fovea for 4° is parafovea. Combining the fovea and parafovea forms an approximately 10° wide area of the retina which we call the visual acuity area. During a fixation, this area takes in the majority of visual information; furthermore, very limited amounts of visual information are taken in during a saccade as saccadic suppression limits the amount of moving information we are able to perceive, so that retinal smearing is not experienced (Irwin 1993). Therefore, fixations and saccades constantly occur in order that we build up a mental representation of the visual environment. The range of visual acuity is wide enough to tolerate the distance between the gaze and the mouse cursor, but the distance beyond this threshold is perhaps not tolerable during this task. The k_y value is about 0.89 as presented in Table 1, indicating that gaze trajectory covers only 89% of cursor trajectory, which supports this assumption. Moreover, given that human peripheral vision is good at detecting dynamic movements (McKee and Nakayama 1984), and the only requirement of the task is to keep the sphere moving along the trace where too much detailed information is dispensable for completing the task, tracing accuracy in the task was not affected without looking directly at where the sphere and the mouse cursor were.

4.5. Limitations and implications

This study investigated the relationship between perceptual complexity and gaze-mouse coordination but various other factors could be taken into account, such as content saliency. While this is an initial investigation, strong conclusions cannot be formulated, so further investigations into other variables which may also influence the results need to be considered in the future.

Although the order of trials in one trial set has been carefully designed so that the same conditions were not shown continuously, the same order of trials was still repeated in each trial set. As subjects repeated the trials ten times, there were practice effects where their performance on the task gradually improved; this was especially noticed in the first condition (the straight line with low gaze-mouse coordination demands). We also found fluctuation of performance caused by the discontinuity between each trial set. However, by removing the first three trials of each trial set the practice effects and unstable performance became insignificant. A Latin square design (Anon. 2008) is suggested in this type of experiment to achieve randomisation without repetition.

Occasionally the device lost tracking of eyes such as blinks. These data have been removed from the analysis, but there is a possibility that trivial bias has been introduced into the results due to the incomplete trial data and trace-shape sensitivity in lead effect evaluation.

A very large gaze-mouse distance has been observed in several subjects' experimental data, possibly because the visual trace and sphere were easy to detect within peripheral vision. According to Fitts' Law (Fitts 1954) and its extension to trajectory-based tasks (Accot and Zhai 1997), shrinking the size of the sphere may increase the difficulty of the task and gaze-mouse coordination demands, and correspondingly change the distance between gaze and mouse. Moreover, Jiang et al. (2015) studied the correlation between pupil dilation and continuous pointing task difficulty using Fitts' law to quantitatively define the complexity of the motor task, which can be adopted in our future work to model the conditions in a more controlled way.

This study serves as a preliminary work for future research to conduct more complicated tasks where a haptic interface may be involved. Haptic devices are used as pointing tools for interacting with 3D virtual reality. Therefore, we intend to extend this work into 3D environments, where we can explore the interaction of vision and haptic feedback.

The performance of human computer interaction applications has the potential to be improved using gaze leading features, especially for visually stimulated applications that are mainly controlled by pointing devices, in which gaze can deliver a reliable prediction of manipulation area. The prediction provides the possibility of pre-computation for real-time display of complex graphic and force feedback. A task with high gaze-mouse coordination demands would benefit more according to our results because high gaze-mouse coordination demanding tasks allow more lead time. Meanwhile, the gaze lead may not always be effective as the pointing device can be leading in low gaze-mouse coordination demanding tasks.

The observed backshoot in the saccade data also provides potential directional information for saccadic movement prediction. Evidence shows that microsaccade direction can reveal the direction of covert attentional shifts by moving away from the visual cue (Engbert and Kliegl 2003). This mechanism may explain the observed backshoot oculomotor behaviour, but there is somewhat of a dispute regarding this in the literature (Tse et al. 2004).

Arguments exist that gaze cannot always overtly represent attention or region of interest because of covert attentional orienting (Posner 1980). However, according to perceptual load theory (Lavie et al. 2004), which proposes that distractor interference can be reduced or excluded from perception when the level of cognitive load in processing task-relevant stimuli is sufficiently high to exhaust perceptual capacity, gaze is more intensively linked to current attention in a task with high cognitive load.

Finally, the strong correlation features between gaze and mouse movements can be extracted from the collected data for visuomotor behaviour modelling, which will, for example, benefit robotic implementation of trajectory-based tasks. The gaze-mouse correlation also forms unique patterns that distinguish it from gaze and mouse movements that are irrelevant to each other. This difference has the potential to be applied in attention decoding for telling whether the user is focusing on the gaze-mouse coordination task or not. Such techniques can be used in a wide range of applications such as adaptive virtual reality, smart mobile devices, and intelligent web applications.

5. Conclusion

In the current study, our first aim was to investigate the spatiotemporal relationship between gaze and mouse movements in a tracing task. To summarise the findings, we showed that, similar to physical eye-hand coordination, there is linearity of gaze-mouse correlation and gaze typically leads the mouse cursor movement with comparable lead time to eye-hand coordination. We also showed a directional asymmetry of lead effect, i.e., leading distance varies if the proportion of horizontal components and vertical components of the trace changes; but the gaze-mouse tracing gain k in the horizontal or the vertical direction is consistent and irrelevant to the trace shape. In addition, the overall distribution of the distance between gaze and mouse cursor is constantly within a typical visual acuity range.

The dependency of gaze-mouse coordination demands in the tracing tasks was then addressed. We validated the hypothesis of a positive correlation between gaze-mouse coordination demands and gaze lead. Clearly, a task with higher coordination demands yields greater lead distance and greater lead time for gaze-mouse coordination. In scenarios such as tasks with extremely low gaze-mouse coordination demands, we found the mouse cursor led the gaze position in the horizontal direction. Yet neither was the tracing gain related to gaze-mouse coordination of the task, nor did overall distance distribution between the gaze and the mouse cursor. Finally, we proposed a new method of lead time calculation, which provided results without directional disparity.

To conclude, the current paper provided the theoretical and analytical explanation of gaze-mouse coordination based on experimental data and our research has provided a complete data set and a framework to analyse the gaze-mouse dependency. The pattern of data provided an indication for how we might improve the design of human-computer interactions with the possibility of more natural interaction based on eye tracking, as well as improve the user experience and alternation of user behaviour where the linear dependency of the mouse and the gaze movements exist. Some applications are available already, e.g., MAGIC pointing technique which uses the gaze information to accelerate the cursor movement (Zhai et al. 1999; Fares et al. 2013), but future research should provide a more complex analysis of practical applications in real human-computer interaction interface designs.

References

Accot, J. and Zhai, S., 1997. Beyond Fitts' law: models for trajectory-based HCI tasks. *In: Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*: ACM. 295-302.

Anon. , 2008. Latin Square Designs. *In: The Concise Encyclopedia of Statistics.* Springer New York, 297-297.

Ariff, G., Donchin, O., Nanayakkara, T. and Shadmehr, R., 2002. A real-time state predictor in motor control: study of saccadic eye movements during unseen reaching movements. *The Journal of Neuroscience*, 22 (17), 7721-7729.

Behan, M. and Wilson, M., 2008. State anxiety and visual attention: The role of the quiet eye period in aiming to a far target. *Journal of Sports Sciences*, 26 (2), 207-215.

Bieg, H.-J., Chuang, L. L., Fleming, R. W., Reiterer, H. and Bülthoff, H. H., 2010. Eye and pointer coordination in search and selection tasks. *In: Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications*: ACM. 89-92.

Biguer, B., Jeannerod, M. and Prablanc, C., 1982. The coordination of eye, head, and arm movements during reaching at a single visual target. *Experimental Brain Research*, 46 (2), 301-304.

Binsted, G., Chua, R., Helsen, W. and Elliott, D., 2001. Eye–hand coordination in goal-directed aiming. *Human Movement Science*, 20 (4–5), 563-585.

Bowman, M., Johannson, R. and Flanagan, J., 2009. Eye–hand coordination in a sequential target contact task. *Experimental Brain Research*, 195 (2), 273-283.

Chen, M. C., Anderson, J. R. and Sohn, M. H., 2001. What can a mouse cursor tell us more?: correlation of eye/mouse movements on web browsing. *In: CHI '01 Extended Abstracts on Human Factors in Computing Systems* Seattle, Washington, 634234: ACM. 281-282.

Coen-Cagli, R., Coraggio, P., Napoletano, P., Schwartz, O., Ferraro, M. and Boccignone, G., 2009. Visuomotor characterization of eye movements in a drawing task. *Vision research*, 49 (8), 810-818.

Crawford, J. D., Medendorp, W. P. and Marotta, J. J., 2004. Spatial transformations for eye-hand coordination. *Journal of Neurophysiology*, 92, 10-19.

de Xivry, J.-J. O. and Lefevre, P., 2007. Saccades and pursuit: two outcomes of a single sensorimotor process. *The Journal of physiology*, 584 (1), 11-23.

Deubel, H. and Bridgeman, B., 1995. Fourth Purkinje image signals reveal eye-lens deviations and retinal image distortions during saccades. *Vision research*, 35 (4), 529-538.

Duchowski, A., 2007. *Eye tracking methodology: Theory and practice*. Vol. 373. Springer.

Engbert, R. and Kliegl, R., 2003. Microsaccades uncover the orientation of covert attention. *Vision research*, 43 (9), 1035-1045.

Fares, R., Fang, S. and Komogortsev, O., 2013. Can we beat the mouse with MAGIC? *In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* Paris, France, 2466183: ACM. 1387-1390.

Fitts, P. M., 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, 47 (6), 381.

Gauthier, G. M., Vercher, J. L., Mussa Ivaldi, F. and Marchetti, E., 1988. Oculo-manual tracking of visual targets: control learning, coordination control and coordination model. *Experimental Brain Research*, 73 (1), 127-137.

Gielen, C. C. A. M., Dijkstra, T. M. H., Roozen, I. J. and Welten, J., 2009. Coordination of gaze and hand movements for tracking and tracing in 3D. *cortex*, 45 (3), 340-355.

Gowen, E. and Miall, R. C., 2006. Eye–hand interactions in tracing and drawing tasks. *Human Movement Science*, 25 (4–5), 568-585.

Guo, Q. and Agichtein, E., 2010. Towards predicting web searcher gaze position from mouse movements. *In: CHI'10 Extended Abstracts on Human Factors in Computing Systems*: ACM. 3601-3606.

Irwin, D. E., 1993. Perceiving an integrated visual world. *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience*, 121-142.

Jiang, X., Zheng, B., Bednarik, R. and Atkins, M. S., 2015. Pupil responses to continuous aiming movements. *International Journal of Human-Computer Studies*, 83, 1-11.

Johansson, R. S., Westling, G., Bäckström, A. and Flanagan, J. R., 2001. Eye–hand coordination in object manipulation. *The Journal of neuroscience*, 21 (17), 6917-6932.

Kapoula, Z. and Robinson, D., 1986. Saccadic undershoot is not inevitable: saccades can be accurate. *Vision research*, 26 (5), 735-743.

Lavie, N., Hirst, A., de Fockert, J. W. and Viding, E., 2004. Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, 133 (3), 339.

Liebling, D. J. and Dumais, S. T., 2014. Gaze and mouse coordination in everyday work. *In: Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*: ACM. 1141-1150.

Masia, L., Casadio, M., Sandini, G. and Morasso, P., 2009. Eye-Hand Coordination during Dynamic Visuomotor Rotations. *PloS one*, 4 (9), e7004.

McKee, S. P. and Nakayama, K., 1984. The detection of motion in the peripheral visual field. *Vision research*, 24 (1), 25-32.

Mrotek, L., Gielen, C. C. A. M. and Flanders, M., 2006. Manual tracking in three dimensions. *Experimental Brain Research*, 171 (1), 99-115.

Neggers, S. F. and Bekkering, H., 2000. Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology*, 83 (2), 639-651.

Paulson, D. S., 2010. *Handbook of regression and modeling: Applications for the clinical and pharmaceutical industries*. CRC Press.

Pfeuffer, K., Alexander, J., Chong, M. K., Zhang, Y. and Gellersen, H., 2015. Gaze-Shifting: Direct-Indirect Input with Pen and Touch Modulated by Gaze. *In: Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* Daegu, Kyungpook, Republic of Korea, 2807460: ACM. 373-383.

Posner, M. I., 1980. Orienting of attention. *Quarterly journal of experimental psychology*, 32 (1), 3-25.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A.-S., McNamara, J. O. and Williams, S. M., 2001. Types of eye movements and their functions. *In: Neuroscience.* 2nd edition. Sunderland (MA): Sinauer Associates.

Reina, G. A. and Schwartz, A. B., 2003. Eye–hand coupling during closed-loop drawing: Evidence of shared motor planning? *Human Movement Science*, 22 (2), 137-152.

Rodden, K., Fu, X., Aula, A. and Spiro, I., 2008. Eye-mouse coordination patterns on web search results pages. *In: CHI '08 Extended Abstracts on Human Factors in Computing Systems* Florence, Italy, 1358797: ACM. 2997-3002.

Rottach, K. G., Zivotofsky, A. Z., Das, V. E., Averbuch-Heller, L. E. A., Discenna, A. O., Poonyathalang, A. and Leigh, R. J., 1996. Comparison of Horizontal, Vertical and Diagonal Smooth Pursuit Eye Movements in Normal Human Subjects. *Vision research*, 36 (14), 2189-2195.

Savitzky, A. and Golay, M. J., 1964. Smoothing and differentiation of data by simplified least squares procedures. *Analytical chemistry*, 36 (8), 1627-1639.

Smith, B. A., Ho, J., Ark, W. and Zhai, S., 2000. Hand eye coordination patterns in target selection. *In: Proceedings of the 2000 symposium on Eye tracking research & applications* Palm Beach Gardens, Florida, USA, 355041: ACM. 117-122.

Tchalenko, J. and Chris Miall, R., 2009. Eye–hand strategies in copying complex lines. *cortex*, 45 (3), 368-376.

Tramper, J. J. and Gielen, C., 2011. Visuomotor coordination is different for different directions in three-dimensional space. *The Journal of neuroscience*, 31 (21), 7857-7866.

Tse, P. U., Sheinberg, D. S. and Logothetis, N. K., 2004. The distribution of microsaccade directions need not reveal the location of attention: reply to Rolfs, Engbert, and Kliegl. *Psychological Science*, 708-710.

Vercher, J. L. and Gauthier, G. M., 1992. Oculo-manual coordination control: Ocular and manual tracking of visual targets with delayed visual feedback of the hand motion. *Experimental Brain Research*, 90 (3), 599-609.

Wang, Y. and MacKenzie, C. L., 1999. Effects of orientation disparity between haptic and graphic displays of objects in virtual environments. *In: INTERACT*. 391-398.

Xia, R. and Barnes, G., 1999. Oculomanual Coordination in Tracking of Pseudorandom Target Motion Stimuli. *Journal of Motor Behavior*, 31 (1), 21-38.

Yamaguchi, S., Konishi, K., Yasunaga, T., Yoshida, D., Kinjo, N., Kobayashi, K., Ieiri, S., Okazaki, K., Nakashima, H. and Tanoue, K., 2007. Construct validity for eye–hand coordination skill on a virtual reality laparoscopic surgical simulator. *Surgical endoscopy*, 21 (12), 2253-2257.

Zhai, S., Morimoto, C. and Ihde, S., 1999. Manual and gaze input cascaded (MAGIC) pointing. *In: Proceedings of the SIGCHI conference on Human factors in computing systems*: ACM. 246-253.