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Abstract

The accuracy and precision of target-directed aiming is contingent upon the availability of online visual feedback. The present study aimed to examine the visual regulation of aiming with blurred vision. The aiming task was executed using a stylus on a graphics digitizing board, which was translated onto a screen in the form of a cursor (representing the moving limb) and target. The vision conditions involved the complete disappearance or blur of the cursor alone, target alone, and cursor+target. These conditions involved leaving the screen uncovered or covering with a diffusing sheet to induce blur. The distance between the screen and sheet was increased to make the blur progressively more severe (0 cm, 3 cm). Results showed significantly less radial and variable error under blurred compared to no vision of the cursor and cursor+target. These findings were corroborated by the movement kinematics including a shorter proportion of time to peak velocity, more negative within-participant correlation between the distances travelled to and after peak velocity, and lower spatial variability from peak velocity to the end of the movement under blurred vision. The superior accuracy and precision under the blurred compared to no vision conditions is consistent with functioning visual regulation of aiming, which is primarily contingent upon the online visual feedback of the moving limb. This outcome may be attributed to the processing of low spatial-high temporal frequencies. Potential implications for low vision diagnostics are discussed.

Keywords: aiming; accuracy and precision; blurred vision; low vision; peripheral vision

1. Introduction

Numerous investigations of target-directed aiming have indicated a substantial contribution of visual feedback for the online control of movement. Indeed, it has been shown that there is superior accuracy and precision when there is standard vision compared to no vision during the movement (Carlton, 1981; Chua & Elliott, 1993; Keele & Posner, 1968; Khan, Franks, & Goodman, 1998; Proteau, Marteniuk, Girouard, & Dugas, 1987; Woodworth, 1899; Zelaznik, Hawkins, & Kisselburgh, 1983). In addition, there is evidence to indicate rapid corrections during aiming movements following a sudden visual perturbation to the limb or target position (Cressman, Franks, Enns, & Chua, 2006; Franklin & Wolpert, 2008; Goodale, Pélisson, & Prablanc, 1986; Heath, Hodges, Chua, & Elliott, 1998; Proteau, Roujoula, & Messier, 2009; Saunders & Knill, 2003; Smeets & Brenner, 1995). While highly informative to theoretical constructs and practical considerations of how typical individuals utilise standard vision within movement, it remains unclear precisely how movements may be adapted to degraded visual contexts including blur or poor visual acuity.

To answer this question, it could be informative to consider the existing evidence of how individuals adapt their aiming movement under no visual feedback. For example, it has been shown that individuals tend to prolong their reaction times, which may indicate some refinement of the initial pre-programming of the movement (Hansen et al., 2006). In addition, participants tend to reduce their force-output, and consequently within-participant spatial variability, which may partially compensate for the lack of visually-regulated online corrections toward the end of the movement (Elliott, Chua, Pollock, & Lyons, 1995; Khan, Elliott, Coull, Chua, & Lyons, 2002). This is consistent with a decrease in the relative time after peak velocity, which is where these online corrections usually occur. Taken together, it appears a greater emphasis is placed on the initial pre-programming in order to contend with the impoverished sensory context. Thus, it is reasonable to suggest that degraded visual information, which compromises the ability to undertake visually-regulated online control, may also manifest in a greater reliance on the initial pre-programming of the movement.

Although somewhat sparse, there is some empirical evidence from individuals with low vision (i.e., poor visual acuity and contrast sensitivity, reduced functional visual fields) undertaking movements that are typically visually-regulated. For example, when performing reach-to-grasp movements, individuals typically extend the time and displacement within both the decelerative phase of the reach component and the final grasp phase after peak grip aperture, which may be attributed to the online correction of movement (Pardhan, Gonzalez-Alvarez, & Subramanian, 2011; 2012; Timmis & Pardhan, 2012a). In a similar vein, when walking to cross obstacles or ascend steps, individuals increase the height and reduce the swing velocity of their lead leg in order to proceed cautiously and reduce the perceived chances of falling (Timmis & Pardhan, 2012b; Timmis, Scarfe, Tabrett, & Pardhan, 2014; see also, Wood et al., 2009). This adaptive response coincides with greater visual search around the key areas related to the target/obstacle (Timmis et al., 2017). Taken together, it appears that rather than completely negating the availability of visual feedback in favour of a purely feedforward approach, individuals may try to accommodate their movements in order to utilise as much vision as reasonably possible.

That said, there is evidence that standard levels of sensorimotor performance can be upheld in conditions where the stimuli and surrounding environment are artificially blurred courtesy of various display technologies (Jackson, Abernethy, & Werrnhart, 2009; Ryu, Abernethy, Park, & Mann, 2018) or plus-diopter lenses (Bulson et al., 2008; Bulson et al., 2015; Basevitch, Tenenbaum, Land, & Ward, 2015; Mann, Abernethy, & Farrow, 2010a, b). Moreover, there is evidence to indicate that the identification of blurred target objects can be slightly enhanced when there is a requirement to move as opposed to being static (Bochsler, Legge, Kallie, & Gage, 2012; Mann et al., 2010b).

The principle explanation for these findings has been adapted from research in visual neuroscience. That is, the magnocellular layers of the lateral geniculate nucleus (LGN) are more sensitive to the low spatial-high temporal frequencies that characterise blurred and dynamic visual experiences (Livingstone & Hubel, 1987; 1988; see also, Hegdé, 2008). For example, single-cell recordings in monkeys indicate an increasing response by the magnocellular layers to a low luminance contrast (Kaplan & Shapley, 1986). Moreover, experimentally-induced lesions of the magnocellular layers have been known to heavily disrupt the sensitivity to low spatial and high temporal frequency gratings (Merigan, Byrne, & Maunsell, 1991; see also, Merigan & Eskin, 1986). This sensitivity can be linked to the visual characteristics associated with visually-regulated movement, which can be attributed to functionally specialised regions within the extrastriate cortex; namely, the dorsal visual pathway culminating in the parietal lobe (Milner & Goodale, 1995; Ungerleider & Mishkin, 1982; Zeki, 2001). Indeed, neuropsychological case studies that feature a lesion along this pathway (occipitoparietal area) reveal problems for visually-regulated movement (optic ataxia), while still retaining aspects of static visual function (Goodale et al., 1994).

The aim of the present study was to more closely explore the influence of blurred vision of the moving limb and target within aiming movements. The present study had participants execute rapid target-directed aiming under conditions of standard, blurred or no vision. Visual stimuli were blurred courtesy of a polypropylene sheet that was placed at different distances from the display in order to progressively modulate the level of blur. In this regard, increasing the separation between the sheet and display increased the perceived blur. This sheet serves as a low-pass filter, and has been preferred to defocusing lenses owing to the fact that it mitigates potential issues with refractive error (e.g., Burton et al., 2015) (see also, Strasburger, Bach, & Heinrich, 2018). The blurred and no vision conditions were simultaneously or separately implemented on the target and moving limb (represented by a cursor). Our expectation was that although static visual acuity may be attenuated, the sensitivity toward low spatial-high temporal frequencies would enable visually-regulated online control to maintain endpoint accuracy and precision whenever the moving limb was blurred. As a further indication of feedback-based control, these findings were predicted to coincide with a shorter reaction time and proportion of time to peak velocity (or longer time afterward).

2. Method

2.1. *Participants*

Ten participants (age range = 19-40 years; male = 9; female = 1) volunteered for the study (for similar sample characteristics, see Cheng, Luis, & Tremblay, 2008; Grierson, Gonzalez, & Elliott, 2009; Heath, Westwood, & Binsted, 2004). All participants were right-handed (based on self-report), had normal or corrected-to-normal vision, and clear of any neurological condition. The study was approved by the local research ethics committee and designed and conducted in accordance with the Declaration of Helsinki (2013).

2.2. Apparatus, task and stimuli

Stimuli were presented on an LCD computer monitor (47.5 x 27.0 cm; temporal resolution = 75 Hz; spatial resolution = 1280 x 800), which was elevated so screen-centre was at the participants' eye level. An 800 μ polypropylene sheet was placed in front of the screen using a combination of cardboard spacers and adhesive fabric strips (Velcro, Manchester, NH, USA). This sheet acted as a low-pass filter, which progressively blurred the screen image when it was placed further away from the screen (for similar procedures, see Burton et al., 2015). A GTCO Calcomp Drawing Board VI (temporal resolution = 125 Hz, spatial resolution = 1000 lines per inch) was installed below and in front of the screen. All testing was undertaken in a dark laboratory setting.

A static visual acuity test was performed using the Freiburg Visual Acuity and Contrast Test (FrACT; Bach, 1996). Participants were sat at a 2-m test distance from the screen, and generated a forced-choice response to the direction of the gap of a Landolt-C ring by using a numeric keypad that was connected via a universal serial bus (USB) extension cord. The gap would assume one of 8 possible directions, while the required responses were illustrated by arrows that overlaid the numbers on the keypad (1 = left-down, 2 = down, 3 = right-down, 4 = left, 6 = right, 7 = left-up, 8 = up, 9 = right-up).

A left-to-right target-directed aiming movement was undertaken by translating a stylus with the right upper-limb as quickly and accurately as possible. Participants were sat at a 70-cm distance from the screen (see Fig. 1). Vision of the limb was occluded by placing an adjustable shelving unit over the graphics digitizer board, while the stylus position was translated to the screen. The home (2-cm; ~1.6°), target (1-cm; ~.82°) and cursor (1-cm; ~.82°) that represented the stylus position were presented as square objects. Both the home and target objects were coloured in grey, although the home object would turn to green at trial onset (see *Procedures*). The cursor was always coloured in black, while the background was white. Displacement between the home and target positions was always 27 cm (~21°; centre-to-centre).

2.3. Procedures

Participants completed the entire procedure within a single 60-min visit to the laboratory. The static visual acuity test was conducted while the screen was uncovered or had a polypropylene sheet placed in front of it using adhesive fabric strips. The sheet could be placed on the screen at a 0-cm separation or with cardboard spacers affixed to the edges of the screen such that there was a 3-cm separation. Each administration of the test comprised 18 trials. In order to evaluate the potential of adaptation (Kalloniatis & Luu, 2007), these measures were taken at both the start and end of the laboratory session.

Following the completion of the first vision test, participants were familiarised with the stylus and graphics digitizer board by completing a single aiming trial. A trial commenced with the presentation of a grey-coloured home object. Therein, participants had to place the stylus into an indented cardboard texture that was attached to the graphics digitizer board (for similar procedures, see Proteau et al., 2009), which equated to the position of the home object on the screen. This texture acted as a guide (somatosensory) for the stylus to reach the home position in the absence of visual feedback between trials. To indicate that participants were ready to commence the trial, they would press-and-release the tip on the stylus pen. Following an 800-2300 ms foreperiod, the home object would turn green, while the cursor and target would also appear in order to signal the start of the trial. Participants had to try to place any portion of the cursor over the centre of the target as quickly and accurately as possible. On trials with visual feedback, both the cursor and target remained visible throughout the aiming movement, and then disappeared once the movement was completed, and the tip of the stylus was pressed. Conversely, on trials with no visual feedback, the cursor and target disappeared as soon as the cursor moved beyond the home position and remained so throughout the trial. The cursor and target remained invisible while participants relocated the stylus back in the cardboard texture that coincided with the home position. The target reappeared when the tip of the stylus was pressed to commence the next trial. Importantly, the absence of any augmented or terminal feedback for all of the conditions ensured any possible effects could be isolated to the online control of movement.

In a similar vein to the static visual acuity test, each block of trials involved the screen being uncovered or covered by a polypropylene sheet with a 0- or 3-cm separation from the screen. When the screen was uncovered, the different portions of the stimuli were systematically made to disappear following movement onset. That is, the cursor and target would both be visible, the cursor and target would both disappear, only the cursor and not the target would disappear, or only the target and not the cursor would disappear (see Fig. 2). When the sheet was in front of the screen, both the cursor and target stimuli were always presented and were not made to disappear. The sheet could cover both the cursor trajectory and target position, only the cursor trajectory and not the target position, or only the target position and not the cursor trajectory. Covering the cursor alone involved placing the sheet between the far left of the screen near the home position to within 5 cm of the target (0-22 cm amplitude; ~4-21°). Covering the target alone involved placing the sheet between 5 mm short of the target and the far right of the screen that was beyond the target (22-27 cm amplitude; ~0-4°). Thus, covering the cursor trajectory mostly consisted of the early initial impulse, while covering the target position consisted of any late corrective adjustments (Elliott et al., 2014; Khan & Franks, 2003; Lawrence, Khan, Buckolz, & Oldham, 2006;).

There were 10 blocks of trials, which each pertained to a separate condition (standard vision, no vision-cursor+target, no vision-cursor, no vision-target, 0 cm-cursor+target, 0 cm-cursor, 0 cm-target, 3 cm-cursor+target, 3 cm-cursor, 3 cm-target) (see Fig. 2). There were 15 trials per block with the first 5 trials of each block being regarded as familiarisation/practice (total number of trials = 150 trials). Any trials that featured a reaction time that was <100 ms or >1500 ms were discounted and forced to be repeated within the experiment.

[Insert Figure 1 and 2 about here]

2.4. Data Management and Analysis

Visual acuity scores were expressed as logMAR, which involves the logarithmic transformation of the ratio between the standard and participant minimum angle of resolution (MAR): log10 (standard MAR / participant MAR).

The last 10 movement trials from each block were forwarded for processing. Cartesian coordinates from the graphics digitizer board were smoothed using a second-order, dual-pass Butterworth filter with a low-pass cut-off frequency of 8 Hz. Instantaneous velocity from the resultant vector was obtained using the three-point central difference method. Movement onset was determined as the first moment when the velocity reached ≥20 mm/s, while movement offset was determined as the subsequent moment when velocity reached between <10 mm/s and >–10 mm/s. This criteria was broadly consistent with previous studies (e.g., Hansen et al., 2006; Khan et al., 2002; Robinson, Elliott, Hayes, Barton, & Bennett, 2014), while the shift toward a minimum negative velocity at offset captures the potential for zero-crossings near the endpoint (e.g., Dounskaia, Wisleder, & Johnson, 2005; Elliott et al.., 2014; Fradet, Lee, & Dounskaia, 2008; Hsieh, Liu, & Newell, 2017).

Overall performance was measured using reaction time (i.e., time difference between trial and movement onsets), movement time (i.e., time difference between movement onset and offset), radial error (i.e., radial distance between the limb position at movement offset and target-centre) and variable error (i.e., within-participant population (no degrees-of-freedom) standard deviation of radial error scores). In order to examine the relative contribution of pre-programming and online control, we more closely examined the kinematics by initially identifying the moments before and after peak velocity, respectively. Herein, we calculated a series of measures that could be adapted to infer these processes (Khan et al., 2006). Firstly, we calculated the proportion of time to peak velocity (i.e., absolute time to peak velocity / total movement time), where a shorter proportion of time to peak (or longer time afterward) would indicate an increased utilisation of online visual feedback for the correction of errors (Chua & Elliott, 1993; Elliott, Carson, Goodman, & Chua, 1991; Pardhan et al., 2012; Timmis & Pardhan, 2012a). Likewise, we calculated the within-participant correlation between the distances travelled to and after peak velocity, where a more negative relationship would indicate a correction to the movement after peak velocity in order to successfully reach the target (e.g., Elliott, Binsted, & Heath, 1999; Roberts, Wilson, Skultety, & Lyons, 2018). Finally, we calculated spatial variability at peak velocity and movement end (i.e., within-participant standard deviation of displacement at these landmarks) under the assumption that any increase when progressing through the trajectory must be subsequently reversed if indeed the limb is to precisely enter within the target boundaries (Khan, Lawrence et al., 2003; Khan, Franks et al., 2006).

Visual acuity scores were initially analysed by conducting a two-way repeated-measures ANOVA with factors of test (pre-, post-test) and vision (no blur, 0 cm, 3 cm). With regard the movement performance data, as typical visually-regulated limb movements involve vision that is clear (e.g., ≤ 20/20 visual acuity) and full-field (i.e., cursor and target), it is of interest to capture the deviation from this particular context. Thus, we normalized the individual participant values from the experimental conditions by expressing them as a percentage change with respect to the standard vision control condition for each of the dependent measures: (experimental – standard vision control) / standard vision control x 100. Thus, a negative (positive) score would usually indicate a decrease (increase) relative to a standard vision control that is associated with typical visually-regulated movement (N.B., inverse interpretation for the measure of within-participant correlation). Measures were analysed using a two-way repeated-measures ANOVA with factors of vision (0-cm, 3-cm, none) and stimuli (cursor+target, cursor, target). However, the spatial variability measure was alternatively analysed using a three-way ANOVA, which additionally incorporated the factor of kinematic landmark (peak velocity, movement end).

Mauchly's test was used to test the assumption of equal variances (Sphericity) (original (Sphericity-assumed) degrees-of-freedom are reported). In the event of a violation, then the Huynh-Feldt value was adopted when Epsilon was >.75, although the Greenhouse-Geisser value was adopted if it was ≤.75. Significant effects that featured more than two means were decomposed using the Tukey HSD post hoc procedure. Effect sizes were indicated by using partial eta-squared (η_p^2). Additionally, in order to corroborate our main statistical analysis including comparison with the standard vision control, we conducted a series of one-sample t-tests with a test value of zero (representing no change relative to standard vision control) (uncorrected). Significance was declared at $p < .05$.

3. Results

3.1. Optometric Measures

For visual acuity, there was no significant main effect of test, $F(1, 9) = .54$, $p = .48$, $\eta_p^2 = .06$, although there was a significant main effect for vision, $F(2, 18) = 264.78$, $p < .001$, $\eta_p^2 = .97$. Post hoc analysis indicated that the no blur condition was significantly lower (better visual acuity) (logMAR $M = -.10$, $SD = .10$) than the 0 cm condition (logMAR $M = .07$, $SD = .13$), which was also significantly lower than the 3 cm condition (logMAR $M = .63$, $SD = .09$) (Tukey HSD = .07) (see also Fig. 3). There was no significant interaction between test and vision, $F(2, 18) = .32$, $p = .73$, $\eta_p^2 = .03$.

[Insert Figure 3 and Table 1 about here]

3.2. Outcome Measures

Table 1 shows the means for each of the outcome and kinematic measures (for non-normalized data, see the supplementary material). For reaction time, there was a significant main effect of vision, $F(2, 18) = 9.15$, $p = .002$, $\eta_p^2 = .50$, which indicated a significantly shorter time to initiation for the 0-cm and 3-cm blurred conditions compared to the no vision condition (*ps* < .05) (Tukey HSD = 6.28). There was no significant main effect of stimuli, $F(2, 18) = .36$, $p = .70$, $\eta_p^2 = .04$, nor a significant interaction between vision and stimuli, $F(4, 36) = 2.05$, $p = .11$, $\eta_p^2 = .19$. For movement time, there was no significant main effect of vision, $F(2, 18) = 2.67$, $p = .097$, η_p^2 .23, and stimuli, $F(2, 18) = 1.57$, $p = .24$, $\eta_p^2 = .15$, nor a significant interaction between vision and stimuli, $F(4, 36) = .57$, $p = .59$, $\eta_p^2 = .06$.

For radial error, there was a significant main effect of vision, $F(2, 18) = 6.41$, $p = .03$, $\eta_p^2 = .42$, and stimuli, $F(2, 18) = 10.90$, $p = .006$, $\eta_p^2 = .55$, although these effects were superseded by a significant interaction between vision and stimuli, $F(4, 36) = 11.36$, $p = .002$, $\eta_p^2 = .56$ (see Fig. 4A). Post hoc analysis indicated that there was significantly less error for the 0-cm and 3-cm blurred conditions compared to the no vision condition when manipulating the cursor+target and cursor (*ps* < .05), while there were no such differences when manipulating the target (*ps* > .05) (Tukey HSD = 177.08). In a similar vein, variable error revealed a significant main effect of vision, $F(2, 18) = 5.65$, $p = .04$, $\eta_p^2 = .39$, and stimuli, $F(2, 18) = 6.07$, $p = .03$, $\eta_p^2 = .40$, as well as a significant interaction between vision and stimuli, $F(4, 36) = 6.64$, $p = .02$, $\eta_p^2 = .43$ (see Fig. 4B). Post hoc analysis confirmed that there was significantly less variability for the 0-cm and 3-cm blurred conditions compared to the no vision condition when manipulating the cursor+target and cursor (*ps* < .05), while there were no such differences when manipulating the target (*ps* > .05) (Tukey HSD = 239.92).

[Insert Figure 4 about here]

3.3. Online Control Measures

For the proportion of time to peak velocity, there was a significant main effect of vision, $F(2, 18) = 15.60$, $p = .002$, $\eta_p^2 = .63$, which indicated a significantly shorter proportion of time for the 0-cm and 3-cm blurred conditions compared to the no vision condition (*ps* < .05) (Tukey HSD = 7.90). In addition, there was a significant main effect of stimuli, $F(2, 18) = 5.20$, $p = .02$, $\eta_p^2 = .37$, which indicated a significantly longer proportion of time to peak velocity for the cursor+target and cursor manipulations compared to the target manipulation (*ps* < .05) (Tukey HSD = 5.78). However, there was no significant interaction between vision and stimuli, $F(4, 36) = 1.03$, $p = .41$, $\eta_p^2 = .10$.

For the within-participant correlation, there was a significant main effect of vision, $F(2, 18) = 19.36$, $p < .001$, $\eta_p^2 = .68$, and stimuli, $F(2, 18) = 6.06$, $p = .02$, $\eta_p^2 = .41$, although these effects were superseded by a significant interaction between vision and stimuli, $F(4, 36) = 4.21$, $p = .04$, $\eta_p^2 = .32$. In a similar vein to previous measures, there was a significantly more negative correlation for the 0-cm and 3-cm blurred conditions compared to the no vision condition when manipulating the cursor (*ps* < .05), although these differences failed to reach significance when manipulating the cursor+target, and there were no such differences when manipulating the target (*ps* > .05) (Tukey HSD = 39.36).

For spatial variability, there was a significant main effect of vision, $F(2, 18) = 13.02$, $p = .004$, $\eta_p^2 = .59$, and stimuli, $F(2, 18) = 7.08$, $p = .005$, $\eta_p^2 = .44$, although no significant main effect of kinematic landmark, $F(1, 9) = 3.19$, $p = .11$, $\eta_p^2 = .26$. There were significant interactions between vision and stimuli, $F(4, 36) = 5.64$, $p = .003$, $\eta_p^2 = .39$, vision and kinematic landmark, $F(2, 18) = 8.99$, $p = .01$, $\eta_p^2 = .50$, and stimuli and kinematic landmark, $F(2, 18) = 6.81$, $p = .006$, $\eta_p^2 = .43$. These effects were superseded by a significant three-way interaction between vision, stimuli and kinematic landmark, $F(4, 36) = 6.40$, $p = .002$, $\eta_p^2 = .42$ (see Fig. 5). Post hoc analysis confirmed that there were no significant differences at peak velocity (*ps* > .05). However, there was significantly less variability for the 0-cm and 3-cm blurred conditions compared to the no vision condition when manipulating the cursor+target and cursor (*ps* $< .05$), while there were no such differences when manipulating the target (*ps* $> .05$), toward the end of the movement (Tukey HSD = 106.38).

[Insert Figure 5 about here]

In line with the main factorial analysis, the supplementary single-sample t-tests revealed a significant difference between the standard vision control (synonymous with a test value of zero) and no vision of the cursor for each of the dependent measures (range $ts(9) = 2.47\text{-}3.74$, *ps* $< .05$) except movement time ($t(9) = .13$, $p = .99$). Likewise, there was a significant difference between standard vision and no vision of the cursor+target for most of the dependent measures (range $ts(9) = 2.38\text{-}3.13$, *ps* $< .05$), although this difference only approached significance for variable error ($t(9) = 2.14$, $p = .061$) and within-participant correlation ($t(9) = 2.15$, $p = .060$). Further exceptions included movement time ($t(9) = .82$, $p = .43$), and spatial variability at peak velocity ($t(9) = 1.76$, $p = .11$). However, there was no significant difference between standard vision and no vision of the target for any of the dependent measures (range $ts(9) = .56\text{-}1.97$, *ps* $> .05$). Finally, there was never a significant difference between the standard and blurred vision conditions within each of the stimulus manipulations (range $ts(9) = .12\text{-}2.10$, *ps* $> .05$).

4. Discussion

The present study aimed to investigate the influence of blurred vision, and more specifically whether any differences could be attributed to manipulations of the moving limb and/or target that impacted upon the initial pre-programming or visually-regulated online control. Because of the low spatial-high temporal frequency visual inputs that contribute to visually-regulated online control, it was predicted that the typical advantage from visual feedback for the online control of movement may be upheld in the blurred conditions, and thus superior in accuracy and precision than the no vision condition. Consistent with this logic was evidence that the mean and variability of endpoint error was lower under blurred (0 cm, 3 cm) compared to no vision, and mostly when stimuli featured the cursor that represented the moving limb (i.e., cursor, cursor+target). Importantly, this superiority of blurred vision was evident even when the blur was so severe that the individuals' static visual acuity reached levels that would otherwise exceed the criteria for low vision or partial blindness (>.60 logMAR [Royal National Institute for the Blind]; >.30 logMAR [World Health Organization]). Further inspection of the movement kinematics revealed similar differences between the vision conditions in the proportion of time to peak velocity, within-participant correlation between the distances travelled to and after peak velocity, and spatial variability from peak velocity to the end of the movement.

It is well known that aiming in the absence of visual feedback usually causes individuals to prolong their reaction time, increase (decrease) the proportion of time to (after) peak velocity and decrease the spatial variability within the initial trajectory (Hansen et al., 2006; see also, Elliott et al., 1995; Khan et al., 2002). These changes are suggested to manifest from attempts to refine the initial pre-programming and limit the subsequent error within the movement, which can then partially off-set the inability to undertake visually-regulated online control. In other words, a feedforward approach to the movement is adopted whenever the individual becomes aware of, or accustomed to, the absence of visual feedback (Burkitt, Staite, Yeung, Elliott, & Lyons, 2015; Cheng et al., 2008; Cheng, Manson, Kennedy, & Tremblay, 2013; Whitwell, Lambert, & Goodale, 2008). However, the present study indicated that despite the degraded visual context, individuals did not adopt the same feedforward approach within the blurred vision conditions. Instead, they shortened their reaction time and proportion of time to peak velocity (or longer time afterward). Moreover, the more negative within-participant correlation and decreased endpoint variability suggests that the error accumulated within the initial trajectory was corrected toward the end of the movement through the use of online visual feedback (Khan, Lawrence et al., 2003; Roberts et al., 2018; see also, Khan, Franks et al., 2006).

Consistent with this logic was evidence that the advantage of (blurred) visual feedback on the accuracy and precision of aiming movements appeared to be concentrated toward those conditions featuring the cursor (representative of the moving limb). Indeed, even in the absence of the target during the movement, individuals continued to utilise visual feedback of the cursor in order to land nearer the target's original (pre-response) location. Because individuals received the same pre-response visual information pertaining to the surrounding movement environment but no terminal augmented feedback related to the outcome, it is most likely that the online visual feedback of the cursor was adapted in order regulate the ongoing movement of the limb. These findings are consistent with previous studies that have similarly indicated superior accuracy and/or precision when provided with visual feedback of the moving limb compared to the target (Carlton, 1981; Elliott et al., 1991; Ghez, Gordon, & Ghilardi, 1995; Rossetti, Stelmach, Desmurget, Prablanc, & Jeannerod, 1994). While the target may be important for accurate aiming movements, it is possible that this portion of visual information can be sufficiently processed within the pre-response interval and stored for later use within the movement (Coello & Magne, 2000; Elliott, Calvert, Jaeger, & Jones, 1988; Elliott & Madalena, 1987; Velay & Beaubaton, 1986; Westwood & Goodale, 2003).

That said, there are a number of studies that have indicated the presence of a target offers a more important source of visual information than the moving limb (Elliott, 1988; Prablanc, Pélisson, & Goodale, 1986). These apparent discrepancies may be explained by the differences in the provision of terminal feedback. Indeed, previous evidence indicates that while visual feedback within the movement itself may not always contribute to online control (i.e., trial n), it can still be used for the pre-programming of subsequent aiming movements (i.e., trial n+1) (Abahnini, Proteau, & Temprado, 1997; Bard, Paillard, Fleury, Hay, & Larue, 1990; Khan & Franks, 2003; Khan, Lawrence, Franks, & Buckolz, 2004). However, in the context of the present study, it is important to recognise that each of the conditions featured the same restricted terminal feedback. This experimental control was designed to isolate any potential differences to the use of online visual feedback. Thus, it is possible that the absence of terminal feedback across each of the vision conditions may have negated any possible advantage served by vision of the target (e.g., spatial error between the movement end and target position). At the same time, we cannot disregard other methodological differences including the sensorimotor environment (e.g., real vs. digitized set-up), and availability or time-course of pre-response visual information (e.g., cursor vs. target, 0 vs. 2 sec).

Of interest, the previously stated differences between the vision conditions as a function of the stimuli failed to unfold for the temporal measures. For example, there were limited differences between the vision conditions in the overall movement time, which suggests it was not necessarily influenced by the previously stated use of online visual feedback (for examples of visually-regulated online control independent of a processing time-lag, see Cressman et al., 2006; 2007; Grierson & Elliott, 2008) but perhaps the uniform or constant presentation of the stimuli during the pre-response interval (e.g., amplitude, target size; Fitts, 1954; Fitts & Peterson, 1964). Moreover, there was a shorter reaction time and proportion of time to peak velocity for blurred compared to no vision, which was independent of the stimuli. That is to say, the time it took to pre-programme and complete the initial impulse of the movement when there was no vision of the target began to resemble or come closer to the conditions with no vision of the cursor and cursor+target. In this regard, we may speculate that despite the importance of online visual feedback of the cursor, the absence of the target within the movement means that there was perhaps slightly more reliance upon pre-programming. Specifically, individuals had to adapt the initial presentation of the target in order to form or parameterize an adequate movement attempt before the target was extinguished and they were no longer able to make direct reference to it during the movement (Elliott & Madalena, 1987). That said, these suggestions warrant some degree of caution because the trend in the proportion of time to peak velocity appeared to be consistent with that of the findings for spatial accuracy and precision. That is, there was a tendency to shorten the proportion of time (indicating less online control) in only those conditions with online visual feedback of the cursor.

What is consistent throughout the findings, however, is the ability to utilise blurred visual feedback for the online control of movement. Despite this degraded visual context, we may attribute this ability to the unique neural architecture that specialises in different categories of visual information. Specifically, blurred vision can be characterised by low spatial-high temporal frequencies that are more readily processed by the magnocellular layers of the LGN (Livingstone & Hubel, 1987; 1988; Merigan et al., 1991). This visual information is synonymous with the characteristics of online visual feedback for movement, which has been primarily attributed to the dorsal visual pathway (Milner & Goodale, 1995; see also, Goodale & Milner, 2018). Because the magnocellular layers receive visual inputs from the peripherally-distributed rod photoreceptors (via parasol retinal ganglion cells) (Lee, Martin, & Grünert, 2010), and the eyes typically move away from the limb to fixate on the distant target (Helsen, Elliott, Starkes, & Ricker, 1998; Land, 2009), this visual information may have been gleaned from the peripheral visual field. Herein lies the potential to make online corrections to the limb's velocity and direction (Elliott et al., 2017; see also Bard, Hay, & Fleury, 1985; Paillard, 1996).

The present findings concur with a growing trend across the literature that recognises the resilience to blur within visually-regulated movement performance (Allen et al., 2018; Bulson et al., 2015; Krabben et al., 2021; Mann et al., 2010a, b). While the previously identified differences in movement kinematics between standard and low vision are undeniable (Pardhan et al., 2011; 2012; Timmis & Pardhan, 2012a), it is possible that such differences may be partially attributed to a cautious movement strategy that seeks to compensate for any perceived pitfalls in visually-regulated online control (Zult, Allsop, Timmis, & Pardhan, 2019). Thus, further investigations may benefit from alternatively constraining the time that is available to complete the movement (Schmidt et al., 1979; see also, Khan et al., 2003; Zelaznik et al., 1983); and in so doing, observe the limits or capacity to utilise degraded visual feedback for online control.

In conclusion, the present findings provide an initial indication that visually-regulated online control within rapid manual aiming can be upheld under a degraded visual context. Consequently, there appears to be quite a degree of resilience to blur within movement control that would otherwise be considered detrimental to static visual acuity. To this end, we may speculate on the potential value in adopting assessments of visual abilities that comprise of more dynamic and functional movement contexts alongside existing diagnostic tools (e.g., Snellen visual acuity, Pelli-Robson contrast sensitivity). Thus, we may come to understand more about the adaptive responses of low vision candidates with a view to developing sensorimotor interventions. Naturally, with this in mind, a more representative sample would be advised compared to the current sub-set that was intended for purely experimental purposes.

Declaration of Interest

None

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Tables

Table 1. Normalized mean (±SE) values for each of the dependent measures as a function of vision (0-cm, 3-cm, none) and stimulus (cursor+target, cursor, target) conditions. Data may be interpreted as a percentage change with respect to the standard vision control.

	cursor+target			cursor			target		
	0-cm	3-cm	none	0-cm	3-cm	none	0-cm	3-cm	none
reaction time	-1.48 (3.78)	.89 (4.27)	18.56 (5.93)	3.91 (3.26)	3.10 (3.79)	11.90 (3.62)	1.91 (5.13)	4.13 (2.81)	7.43 (3.78)
movement time	-2.13 (4.84)	-2.32 (5.46)	-4.75 (5.77)	-.92 (3.76)	1.25 (3.82)	-.89 (6.73)	4.82 (4.39)	4.65 (3.91)	-4.72 (5.81)
radial error	2.82 (10.51)	35.64 (31.60)	518.45 (207.61)	7.28 (11.21)	14.51 (17.10)	449.06 (135.35)	4.05 (23.18)	3.84 (17.27)	176.79 (147.21)
variable error	34.54 (28.53)	82.23 (62.36)	369.18 (172.48)	31.45 (26.71)	47.99 (36.08)	378.67 (153.51)	54.71 (48.45)	39.87 (30.77)	97.19 (74.80)
time to peak velocity	-.79 (3.50)	2.73 (3.42)	14.34 (4.98)	-1.39 (3.04)	2.55 (4.18)	14.24 (5.17)	-4.03 (3.39)	-1.34 (2.62)	2.27 (4.02)
within-participant correlation	12.03 (8.76)	-4.24 (12.06)	-25.86 (12.04)	5.26 (7.72)	1.68 (8.98)	-49.47 (13.23)	13.25 (10.97)	1.47 (11.13)	5.94 (10.41)
spatial variability – peak velocity	26.73 (12.74)	2.90 (10.56)	14.52 (8.25)	15.21 (8.26)	14.28 (8.89)	28.25 (9.56)	11.10 (9.86)	-1.83 (15.08)	17.03 (10.60)
spatial variability – movement end	25.88 (26.00)	93.39 (67.15)	301.04 (126.55)	24.02 (21.05)	59.35 (38.39)	355.57 (106.10)	34.92 (42.58)	38.64 (36.74)	64.82 (55.76)

Figure Captions

Fig. 1 (A) Representative illustration of the experimental set-up including the desk-mounted display area (*black*) with the diffusing sheet attached (*grey*), occluding shelving unit (*white*) and graphics digitizer board with the stylus (*grey*). (B) Also, illustration of the stimulus display including the home (*left, grey*), cursor (*black*) and target (*right, grey*) objects (*upper panel*). The cursor translated the movement of the stylus (*grey*) from the graphics digitizer board (1:1 mapping), which was initiated from the position of an indented cardboard texture (*left, grey*) that aligned with the home object on the screen (*lower panel*).

Fig. 2 Representative illustration of the experimental conditions. Small *black* and *grey* squares represent the home and target positions, respectively. Standard vision condition is presented separately as it was a reference for normalizing all other conditions (see *Data Management and Analysis*). Rectangular shaded panels indicate the stimulus areas covered by the diffusing sheet with changes in opacity representing the severity of blur. *Filled* and *unfilled* (with *dotted* lines) squares represent the visual presentation and disappearance of stimuli, respectively.

Fig. 3 Physical size of the optotypes that equated to the mean visual acuity for 3-cm, 0-cm and standard no blur manipulations (in order from left-to-right).

Fig. 4 Normalized mean (A) radial and (B) variable error as a function of vision (0-cm, 3-cm, none) and stimulus (cursor+target, cursor, target) conditions. Error bars represent the standard error of the mean (zero equates to no change from the standard vision control).

Fig. 5. Mean spatial variability at peak velocity and movement end (with minor jitter of data points for purposes of clarity) under the different vision conditions (see legend) within the cursor+target (left panel), cursor (middle panel) and target (right panel) stimulus conditions. For reference to typical visually-regulated movement, the *triangle* symbols within each panel indicate variability under the standard vision control.