Examining the spatiotemporal disruption to gaze when using a myoelectric prosthetic hand

Parr, JVV[1]., Vine, SJ[2]., Harrison, NR[3]., & Wood, G[4]

[1.] School of Health Sciences, Liverpool Hope University, Liverpool, UK

[2.] College of Life & Environmental Sciences, University of Exeter, Exeter, UK

[3.] Department of Psychology, Liverpool Hope University, Liverpool, UK

[4.] Centre for Health, Exercise and Active Living, Manchester Metropolitan University, UK

Corresponding Author:
Dr Greg Wood
Manchester Metropolitan University
MMU Cheshire
Crewe Green Road
CW1 5DU
Tel: 0161 247 5461
Email address: greg.wood@mmu.ac.uk

Abstract

The aim of this study was to provide a detailed account of the spatial and temporal disruptions to eye-hand coordination when using a prosthetic hand during a sequential fine motor skill. Twenty-one abled-bodied participants performed 15 trials of the ‘picking up coins’ task derived from the Southampton Hand Assessment Procedure (SHAP) with their anatomic hand and with a prosthesis simulator while wearing eye-tracking equipment. Gaze behaviour results revealed that when using the prosthesis, performance detriments were accompanied by significantly greater hand-focused gaze and a significantly longer time to disengage gaze from manipulations to plan upcoming movements. Our findings highlight key metrics that distinguish disruptions to eye-hand coordination that might have implications for the training of prosthesis use.

Keywords: eye-hand coordination, prosthesis, amputee, visuomotor control, visual attention

1. Introduction

The human hand represents a prehensile tool that enables us to interact with our environment through a complex repertoire of sophisticated movements (Clement, Bugler, & Oliver, 2011). The sensory structure of the hand contains a high density of mechanoreceptors that provide haptic feedback regarding the geometric properties of a grasped object (Brand, 1985), enabling fine control of grip forces and the detection of grip slippage (Cohen, 1999). It is therefore no surprise that the loss of a hand and its subsequent disruption to eye-hand coordination can significantly impact the ease with which day-to-day activities are performed following the introduction of a myoelectric prosthesis (Pasluosta, Tims, & Chiu, 2009). As well as managing the significant reductions in degrees of freedom, proprioception and haptic feedback, the difficult challenge for users is to re-learn how to control their new 'hand' with different muscle groups (via electrodes) and neural pathways from those used in the anatomical hand (Bouwsema, Kyberd, Hill, van der Sluis, & Bongers, 2012). This process demands high levels of attention during grasping activities, leading to a high conscious burden for users (Carrozza et al., 2001) and high rejections rates of these types of devices (Williams & Walter, 2015).

To understand the challenges that an amputee faces when attempting to relearn these skills it is worth examining the role that vision plays in the development of eye-hand coordination. Evidence suggests that newborn human infants attempt to view their hands when reaching for objects in the early stages of development (van der Meer, van der Weel, & Lee, 1995; van der Meer, 1997) although human adults rarely fixate the hand when reaching and grasping (Johansson, Westling, Bäckström, & Flanagan, 2001; Land, Mennie, & Rusted, 1999; Pelz & Canosa, 2001). Burnod et al. (1999) proposed that this reliance on vison to monitor the moving hand (as seen in infants) represents an important stage in learning visuomotor transformations in the context of reaching and grasping. By closing the visual-manual loop, initial sensorimotor mapping rules between commands and movements and between vision and proprioception are explored and learned (von Hofsten, 2004). After these rules have been established typical reaching and grasping involves the eyes leading the hands, playing a proactive and sequential role in supporting the performance of tasks of daily living. For example, Land et al**.** (1999) found that the eyes often move onto a subsequent 'to-be-grasped' object about half a second before manipulation of a current object is complete. In effect, they are able to disengage visual attention from action as soon as another sense (i.e., proprioception) can take over from it. Therefore, the development of eye-hand coordination is characterised by an early reliance on visual information to guide hand movements and object manipulations that relinquishes to more proprioceptive modes of control as the eyes start to precede hand movements and coordination develops (Sailer, Flanagan, & Johansson, 2005).

Therefore, when an individual suffers an amputation and is fitted with a hand prosthesis it is likely that the previously acquired sensorimotor mapping rules related to the control of their anatomical hand are lost or become redundant. Consequently, an amputee may be forced to reinvest in primitive control processes resulting in a corresponding reliance on vision to monitor and control prosthetic hand movements. Vision then reverts from a feedforward to a feedback resource (Sailer et al., 2005) and is used to supervise on-going actions as opposed to planning future actions ahead of time. In fact, previous research has found support for this disruption to 'normal' eye-hand coordination in studies exploring skilled tool use and prosthetic hand use.

For example, in laparoscopic surgery tasks - a skill that is similar to prosthesis use as it requires the manipulation of a 'tool' that is external to the body and has limited proprioceptive feedback – researchers have shown that novice surgeons spend more time fixating the surgical tool rather than to-be-grasped objects (Vine, Masters, McGrath, Bright, & Wilson, 2012; Wilson et al., 2010). In contrast, experienced surgeons use a "target-focused” gaze strategy where they focus on the object that needs to be manipulated (Wilson et al., 2010). In prosthetic hand use, Sobuh et al. (2014) highlighted key differences in gaze strategies of individuals when using their anatomic hand compared to when using a prosthetic hand**.** In their study, anatomically intact participants devoted more of their attention to the hand and grasping critical areas when using a prosthetic simulator than when using their intact hand during a discrete carton-pouring task. Additionally, they made more saccadic transitions between areas of interest when using the prosthesis simulator, reflecting more erratic and novice-like gaze behaviour (Hermens, Flin, & Ahmed, 2013). In a study examining the visuomotor behaviours of experienced upper limb prosthesis users, Bouwsema et al. (2012) revealed that although users focused their gaze on the object to be grasped for the majority of the task (“target-focused”), there was still a tendency to switch between the object and the hand during performance. The results of these studies indicate that increased visual dependency in the early development of tool use reflects compensatory strategies in the absence of proprioception.

Whilst research thus far has distinguished differences in gaze behaviour between anatomic and prosthetic hand use (Bouwsema et al., 2012; Sobuh et al., 2014), findings have been limited to reporting overall percentages of fixations dedicated to each individual area of interest (AOI) and to assessing the number of transitions between these spatial locations. These measures, although revealing, do not examine the temporal coupling between vision and action and therefore ignore the vital role that vision plays in planning, guiding and controlling movements in sequential movements typical of activities of daily living. Furthermore, as these studies have been limited to single object reach and grasp activities it is unknown how visuomotor control is utilised during more difficult tasks that require greater levels of fine motor control. Therefore, to further understand the disruption to eye-hand coordination in prosthetic hand use then more detailed information is needed regarding the coupling of hand and eye movements as they support successful task execution in actions requiring high levels of dexterity.

The aim of the present study was therefore to explore the disruption to eye-hand coordination during prosthetic hand use in a sequential task requiring fine motor control. We hypothesized that participants' performance would be significantly slower compared to when using their anatomical hand. We further hypothesised that these impairments would be underpinned by two specific disruptions to the spatial allocation and temporal orientation of visual attention. First, we predicted that when using the hand prosthesis participants would be significantly more hand-focused throughout all phases of the task, reflecting more fixations dedicated to guiding the hand or objects being manipulated by the hand (Bouwsema et al., 2012; Sobuh et al., 2014). Second, we predicted that reductions in haptic feedback when using a prosthesis would prevent the disengagement of gaze during initial object manipulation previously shown in able-bodied participants (Land et al., 1999), resulting in a significant delay in the time taken to shift gaze away from the manipulation and onto the next task component. Finally, we predicted that disruptions in the spatial and temporal allocation of gaze would be significant predictors of task performance.

2. Materials and methods

2.1 Participants

Twenty-one participants (13 males and 8 females; age $M = 25.32$, $SD = 5.05$ yrs.) volunteered to participate in the study. Sample size estimates were based on previous literature examining skilled and novice gaze behaviour during tool use that had shown significant performance effects (Wilson et al., 2010; Wilson, et al., 2011). All participants were able-bodied, had normal or corrected vision and had no prior experience with a prosthesis simulator. All participants reported to be right handed as indicated by The

Edinburgh Handedness Inventory (Oldfield, 1971). The study was approved by the local ethics committee and written informed consent was given prior to testing.

2.2 Apparatus

2.2.1 Prosthetic hand

The prosthesis used in this study was the Bebionic™ (Steeper) fully articulating myoelectric hand with multiple pre-programmed grip positions. In order to fit able-bodied participants, the hand was attached to the end of a carbon fibre trough in which participants' forearm and fist was positioned and fastened with Velcro straps (Fig 1). Like most myoelectric hands, this hand is controlled by muscular contractions detected by two electrodes placed on the extensor (extensor carpi radialis) and flexor (flexor carpi radialis) muscles of the forearm. These electrodes (width 18mm x length 27mm) are high in sensitivity (2000-100,000 fold) and range (90-450Hz) and measure electrical changes ($\geq 10\mu V$) on the skin covering the control muscles. These signals instruct five individual actuators within the hand to provide the desired movements. Activation of the extensors trigger the opening of the hand whereas activation of the flexors trigger the closing of the hand. Although the prosthetic hand can provide 14 selectable grip patterns, the hand was pre-programmed into the 'tripod' grip, as is recommended in the SHAP manual.

2.2.2. The Coin Task

The Southampton Hand Assessment Procedure (SHAP) is a clinically validated hand function test that was developed to assess the effectiveness of upper limb prostheses (Light, Chappell, & Kyberd, 2002). The SHAP is made up of 6 abstract objects and 14 activities of daily living (ADL). For this experiment, we used the *picking up coins* task, which is one of the included ADLs. This sequential task required participants to pick up two 2 pence (2.6cm in diameter) and two 1 pence (2cm in diameter) coins from designated areas on the SHAP board (from right to left) and sequentially drop them into a glass jar located in the centre of the board (Fig 1). Specifically, participants were required to place their hand on the hand mat at the start of each trial, and at a time of their choosing, begin the trial by pressing the button on the timer. Once pressed they were required to sequentially drag each coin to the edge of the table in order to pick them up before dropping them in the jar. Once all coins had been dropped in the jar they were required to re-press the trial timer button to end the trial and replace their hand on the mat. If a coin was dropped during the trial the participant was asked to move on to the next coin while a researcher replaced the coin that was dropped.

2.2.3 Gaze behaviour

Gaze behaviour was measured with an Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye XG gaze registration system that measures eye line of gaze at 30Hz with respect to eye and scene cameras mounted on a pair of glasses. The system consists of a recording device (a modified DVCR) and a laptop (Dell Inspiron 6400) with 'Eye-vision' software installed. A circular cursor, representing 1° of visual angle with a 4.5mm lens, indicating the point of gaze in a video image of the scene (spatial accuracy of ±0.5° visual angle; 0.1° precision) was recorded for offline analysis.

2.3 Procedure

Upon arrival, participants were informed of the purpose of the investigation and were provided with a brief introduction to the testing equipment and apparatus. Each participant then read and completed the informed consent. Participants were then sat comfortably at a table, with their elbows resting at approximately 90 degrees to conform to the SHAP task instructions. The eye tracker was fitted and calibrated by asking participants to direct their gaze to nine different points marked within the scene. The task was then explained and a brief demonstration was given before a full practice was allowed. Participants then performed 15 trials of the coin task with their right anatomic hand (a total of 60 coins). After a brief rest, participants were then fitted with the prosthesis simulator and were allowed to practice sending open and close signals until the participant could consistently (on at least five consecutive occasions) send these signals when instructed. After one full practice trial of the coin task wearing the prosthetic hand simulator, participants then completed 15 full experimental trials. Gaze behaviour was continuously monitored throughout testing and re-calibrated if necessary (approximately every fifth trial).

2.4 Measures

2.4.1 Performance

Performance was measured as the time (in seconds) taken to sequentially place all four coins from right to left into the tin. The timer (and thus task) was initiated and terminated via a button press by the participant.

2.4.2 Gaze data

Video data from the Mobile Eye were analysed offline using Quiet Eye Solutions software (Quiet Eye Solutions Inc.) which provides detailed frame-by-frame coding of the motor action and the gaze behaviour of the performer, creating "vision in action" data (Vickers, 2007). At each frame, the gaze was determined to be lying within one AOI, defined in Fig 1. On occasions where AOIs overlapped, priority was given to the AOI that was initially fixated upon so long as the obscuring AOI did not cause the position of this fixation to change. If gaze shifted from its original position following AOI overlap then priority was given to the now obscuring AOI. To further understand the disruptions to gaze throughout the different phases of the task, the task was broken down into six distinct movement phases;

button press 1 (*B1*), coin reach (*Reach*), coin drag (*Drag*), Lift and drop (*Lift/drop*), button press 2 (*B2*) and hand return (*Hand return*). Fig 2 gives a visual representation of each task phase, defining their given onset and offset. Fixations made outside of AOIs were collectively labelled as "Other". Consistent with previous research (e.g., Vickers & Williams, 2007; Wilson, Vine, & Wood, 2009) gaze analysis was performed on a subset of data (every third trial) resulting in a total of 5 trials and 20 coin pickups per participant.

2.4.3 Target Locking Strategy

To provide an indication of efficient gaze control, we adopted a "target locking strategy" (TLS), previously used by Wilson et al. (2010). This measure is computed by subtracting the percentage of time spent fixating the "tool" (or "hand" for the present study) from the time spent fixating the target. Thus, a more positive score reflects more time fixating on targets whereas a negative score reflects more time spent fixating the hand. A score of '0' reflects equal time spent fixating the hand and targets and represents a 'switching strategy'. For the present study, fixations made towards the hand, or objects being manipulated by the hand, were considered "hand-focused", whereas fixations towards the target object of a current movement phase were considered "target-focused". For example, fixations towards the coin would be considered "target-focused" during the 'reach' phase, but considered "hand-focused" during the 'drag' and 'lift and drop' phases when being manipulated by the hand. Interrater reliability from a sample of 50 coins revealed 94% agreement.

2.4.4 Gaze shifting

In order to examine the temporal sequencing of gaze behaviour we measured the time (in milliseconds) that the eye was ahead of the hand movement. To do this we calculated the time taken to shift attention towards the next task component following the completion of the previous task component. If gaze was shifted to the next target before completion of the previous task phase, then a negative time was recorded, indicating that gaze was ahead of the hand. A positive time reflected the extent to which the eye was behind the action of the hand. This measure therefore quantified the time taken to shift gaze to coin 1 following B1 completion (button to coin), to coin 2, 3 and 4 following Lift and drop completion (jar to coin), to the jar following Drag completion (coin to jar), and to the button at the initiation of B2 (jar to button). The mean time to shift was then calculated for each phase separately. Interrater reliability from a sample of 50 coins revealed 98% agreement.

2.5 Statistical Analysis

All data were first subject to outlier analysis, in which data falling outside 2.2 times the corresponding upper and lower interquartile range were removed from further analysis (Hoaglin & Iglewicz, 1987). A Wilcoxon signed-rank test was used to compare the mean performance time between anatomic and prosthetic hand conditions. For overall AOI fixation percentages, a 2 x 6 repeated measures ANOVA was performed with hand condition (anatomic vs prosthetic) as the between-subjects factor and AOI (Hand, Button, Coin, Jar, Hand mat, Other) as the within-subjects factor. For TLS, a 2 x 6 repeated measures ANOVA was also performed with hand condition as the between-subject factor and task phase (B1, Reach, Drag, Lift and drop, B2, Hand return) as the within-subject factor. For the gaze shifting measure a 2 x 4 ANOVA was performed with hand condition as the between-subject factor and transition between task phases (button to coin, jar to coin, coin to jar, jar to button) as the within-subject factor. Finally, linear regression analysis was then carried out to explore if disruptions in TLS of gaze shifting were significant predictors of performance.

Where sphericity was violated, Greenhouse-Geisser corrections were applied. Effect sizes were calculated using partial eta squared (η_p^2) for omnibus comparisons and Cohen's *d* for pairwise comparisons (Cohen, 2013).

3. Results

3.1 Performance

Results from the Wilcoxon signed-ranks test showed that participants performed significantly slower, $Z = -4.02$, $p < .001$, $d = -5.51$, when using the prosthesis simulator (M = 51.97, SD = 17.27 seconds) compared to when using their anatomic hand (M = 4.73, SD = 0.15 seconds).

3.2 Total AOI Fixation %

No significant main effect was found for hand condition, $F(1, 19) = 0.32$, $p = .577$, $\eta_p^2 = 0.02$, but there was a significant main effect of AOI, $F(5, 95) = 440.85$, $p < .001$, $\eta_p^2 = 0.96$. There was also a significant hand condition x AOI interaction, $F(3.25, 61.83) = 296.87$, $p < .001$, $\eta_p^2 = 0.94$. Follow up paired samples *t*-tests between hand conditions revealed that when wearing the prosthesis, participants dedicated significantly greater visual attention to the hand ($p < .001$), and coin ($p < .001$), and significantly less visual attention to the button, ($p < .001$) *and* jar, ($p < .001$), compared to when using their anatomical hand (Fig. 3).

Post hoc repeated measures ANOVAs within each hand condition revealed a significant difference, $F(2.63, 52.74) = 207.31$, $p < .001$, $\eta_p^2 = 0.91$, in overall percentage of fixation percentage dedicated to each AOI in the anatomic hand condition. Pairwise comparisons revealed that participants dedicated a significantly higher percentage of fixations towards the button than all other AOIs (*ps* < .001) and significantly higher percentage to the coin and jar compared to the hand, hand mat and other AOIs (*ps* < .001). Within the prosthetic hand condition, a significant difference, $F(3.17, 60.14) = 659.06$, $p < .001$, $\eta_p^2 = 0.97$, revealed that participants dedicated a significantly higher percentage of fixations towards the coin compared to all other AOIs (*ps* < .001; Fig 3).

3.3 Target locking strategy

Significant main effects for hand condition, $F(1, 13) = 507.59$, $p < .001$, $\eta_p^2 = 0.98$, and movement phase, $F(5, 65) = 253.37$, $p < .001$, $\eta_p^2 = 0.95$, were found for TLS. Results also indicated a significant condition x movement phase interaction, $F(5, 65) = 115.11$, $p < .001$, $\eta_p^2 = 0.89$. Follow-up paired samples *t*-tests between hand conditions revealed that when wearing the prosthesis, participants exhibited significantly lower target-locking strategies throughout all phases of the task (*p*s < .001) compared to anatomic hand use (Fig 4).

Post hoc repeated measures ANOVAs within each hand condition revealed a significant difference, $F(2.38, 36.91) = 83.71$, $p < .001$, $\eta_p^2 = 0.84$, in TLS score across task phases in the anatomic hand condition. Pairwise comparisons revealed that B1 and Lift and Drop phases had significantly higher TLS compared to the Reach phase (*ps* < .01). Furthermore, the Drag phase scored significantly lower TLS compared to all other task phases (*ps* < .001). For the prosthetic hand condition a significant difference, $F(2.94, 52.82) = 266.24$, $p < .001$, $\eta_p^2 = 0.94$, was found across all task phases. Pairwise comparisons revealed that participants scored significantly lower TLS in the Drag task phase compared to all other phases (*ps* < .001; Fig 4).

3.4 Gaze shifting

A significant main effect of hand condition, $F(1, 12) = 165.67$, $p < .001$, $\eta_p^2 = 0.93$, and movement phase, $F(3, 36) =$, $p < .01$, $\eta_p^2 = 0.39$, was found for the time to shift gaze. Results also indicated a significant hand condition x movement phase interaction, $F(3, 36) = 45.73$, $p < .001$, $\eta_p^2 = 0.79$. Follow up paired samples *t*-tests between hand conditions revealed that when wearing the prosthesis, participants took significantly longer to shift gaze throughout every movement phase of the task compared to their anatomic hand (Fig 5).

Post hoc repeated measures ANOVAs within each hand condition revealed a significant difference, $F(3, 45) = 20.47$, $p < .001$, $\eta_p^2 = 0.58$, in time to shift gaze across task phases in the anatomic hand condition. Pairwise comparisons revealed that participants shifted gaze significantly earlier from the coin to the jar compared to the button to coin ($p < .01$), jar to coin and jar to button (*ps* < .001). Participants also shifted gaze significantly earlier from the button to coin than from the jar to coin ($p < .01$). No other significant differences were found (*ps* > .30). For the prosthetic hand condition a significant difference, $F(3, 51) = 29.64$, $p < .001$, $\eta_p^2 = 0.64$, revealed that participants took significantly longer to shift gaze from coin to jar than from any other movement phase (*ps* < .01). Participants also took significantly longer to shift gaze from button to coin than from jar to button ($p < .001$). No further significant differences were found (*ps* = 1.00; Fig 5).

3.5 Regression Analysis

Linear regression analysis revealed that the measure of gaze shifting was a significant predictor, $R^2 = 0.32$, $b = 0.56$, $p = 0.01$, of performance in the coin task. TLS score did not significantly predict task performance, $R^2 = 0.16$, $b = -0.40$, $p = 0.08$.

4. Discussion

This is the first study to explore the spatiotemporal disruption to eye-hand coordination when using a myoelectric prosthetic hand in a sequential fine motor task. We predicted that when using a prosthetic hand simulator, participants would exhibit significantly poorer performance and that this disruption would be underpinned by disruptions to the spatiotemporal allocation of gaze throughout the task. Confirming our predictions, the use of the prosthesis caused a significant decrease in performance, with the coin task taking on average 10 times longer when participants used the prosthetic hand compared to their anatomical hand. Furthermore, these performance disruptions were underpinned by disruptions to the gaze behaviour of participants.

For the spatial allocation of gaze, data from overall AOI fixation percentages revealed that when using the prosthesis participants dedicated significantly more fixations to the hand and coin. Conversely, when using their anatomical hand, participants dedicated significantly more fixations to the button, jar, and hand mat. Whilst this data provides an overall picture of the spatial allocation of gaze, as reported in previous studies (Bouwsema et al., 2012; Sobuh et al., 2014), there are issues that arise when interpreting such data. For example, Figure 6 displays model gaze sequences taken from an anatomic and prosthesis trial, indicating the spatial and temporal allocation of gaze. Despite the coin receiving a considerable amount of fixations in both conditions, these fixations occur mainly during the Reaching phase for the anatomic condition (target-focused), and mainly during the Drag phase during the prosthesis condition (hand-focused). Thus, analysing the spatial allocation of gaze without considering the task-specific temporal relevance of such fixations may result in a degree of misinterpretation.

Results from our TLS measure indicated that participants directed significantly more visual attention to the hand (lower TLS) throughout every movement phase of the task whilst wearing the prosthesis (Fig 4). Specifically, participants scored significantly lower TLS during the ‘Reach’ and ‘Lift and Drop’ phases. While both phases still received a positive TLS (37% for ‘reach’ and 23% for ‘lift and drop’), this still reflects greater hand-focused gaze compared to anatomic hand use but is more reflective of a gaze ‘switching’ strategy (TLS of 0%) previously reported in similar studies (Bouwsema et al., 2012; Sobuh et al., 2014). There are two possible explanations for this switching strategy. It could be that participants switched their attention between the hand and the target during the ‘Reach’ and

'Lift and Drop' phases to monitor the relationship between motor commands, movements and proprioception in an attempt to develop 'new' sensory mapping rules and better hand control (Sailer et al., 2005). Alternatively, it could be that participants increased their visual attention to the hand when lifting and dropping the coin due to the uncertainty in grip security that hand prosthesis users experience (Chadwell, Kenney, Thies, Galpin, & Head, 2016; Pylatiuk, Schulz, & Döderlein, 2007) due to deficits in haptic feedback that is essential for skilled and dextrous object manipulation (Jenmalm, Dahlstedt, & Johansson, 2000). Finally, participants were almost exclusively hand-focused during the 'Drag' phase of the coin task. While this is also likely to reflect visual dependency in the absence of haptic feedback, this dependency is further compounded by the precision needed when manipulating the coin to hang over the edge of the table and the associated performance cost of dropping the coin of the floor. This is evident from the finding that the 'Drag' phase also resulted in significantly lower TLS than the other task phases during the anatomic hand condition. These findings replicate and extend those of Bouwsema et al. (2012), and Sobuh et al. (2014), to a sequential task requiring greater levels of dexterity and fine motor control.

In terms of the temporal orientation of gaze our data show that when using their anatomic hand participants were able to fixate upcoming targets approximately 45ms before manipulation of the previous object was complete, aligning with previous research that has showed how haptic information enables the disengagement of gaze (Land, 2009). The introduction of a prosthesis resulted in a substantial delay (mean of 313ms) in the time to shift gaze onto the next target in the movement phase following completion of the previous movement phase. This again aligns with the findings of Sobuh et al. (2014) and highlights how reductions in haptic feedback, responsible for encoding information regarding the nature of a manipulation, induce grip uncertainty and visual dependence. However, as these delays in gaze shifting also occurred in the absence of a manipulation, they also reflect the need to visually monitor prosthetic hand movements during the early stages of learning to develop novel sensory mapping rules (Sailer et al., 2005). Importantly, regression analysis highlighted that our gaze shifting measure was a significant predictor of prosthesis task performance. This supports the notion that skilled performance is as dependent on the correct allocation of gaze in time as in space (Tatler, Hayhoe, Land, & Ballard, 2011), and suggests that future research should account for the temporal coupling between hand and eye movements.

Taken together, our results suggest that the disruption to eye-hand coordination when using a prosthesis is characterised by increased hand-focused gaze strategies and a reduced ability to disengage gaze from object manipulations. This prevents the planning of future task-related movements ahead of time leading to a dependency on the online conscious control of the hand and reduced performance. This type of movement control seems indicative of the exploratory or cognitive stage of learning (Fitts & Posner, 1967) where learners explicitly test hypotheses and declarative knowledge concerning movement rules is formulated, placing high demands on cognitive resources (Masters & Maxwell, 2008). Interestingly, this interpretation also resonates with the subjective experiences of prosthetic hand users who report that the high cognitive burden is a primary reason for device dissatisfaction and rejection (Cordella et al., 2016).

A possible intervention that has been shown to reduce this cognitive burden during the early stages of learning is implicit motor learning. Implicit motor learning techniques are designed to prevent the build-up of explicit knowledge during skill acquisition resulting in a low conscious awareness of what is being learned about the execution of this skill. As a consequence, this form of learning has been shown to be less resource intensive than explicit techniques (i.e., movement-related verbal instructions), whilst also producing more resilient performance under high levels of fatigue (Masters, Poolton, & Maxwell, 2008) and task difficulty (Maxwell, Masters, & Eves, 2003). Given that prosthetic hand rejection rates have also been attributed to difficulty and fatigue (Cordella et al., 2016; Pylatiuk et al., 2007), avoiding the involvement of explicit movement processing via implicit learning may offer some clinical benefit for prosthetic hand users. Future research should therefore seek to confirm the level of conscious movement processing during initial prosthetic use and explore the efficacy of implicit learning techniques designed to reduce the cognitive burden associated with this early stage of the rehabilitation process.

Another interesting avenue for future research includes exploring the effectiveness of gaze training interventions, which have also been shown to be a form of implicit motor learning (Vine, Moore, Cooke, Ring, & Wilson, 2013). Training novices to adopt expert like gaze behaviours has been shown to expedite the learning process in a multitude of sport skills (Wilson, Causer, & Vickers, 2015) and to facilitate eye-hand coordination in children with movement disorders (Miles, Wood, Vine, Vickers, & Wilson, 2017; Wood et al., 2017). It is noteworthy that this type of intervention has also been shown to be successful for training novices in laparoscopic surgical skills; a fine motor skill that also requires the use of a tool with diminished proprioceptive feedback (Vine et al., 2012; Wilson et al., 2011). Thus, by adopting expert-like gaze behaviours, prosthesis users may be able to bypass the explicit processes that accompany the sensory-mapping stage of learning and reduce the attentional demands associated with this complex movement. Future research should test the efficacy of gaze training interventions for prosthetic hand users.

Despite these interesting findings, several limitations of the study should be addressed. First, although we have highlighted significant spatial and temporal disruptions to gaze for anatomically intact users of a prosthesis simulator, it is still unclear if these findings are representative of early prosthesis use in upper-limb amputees. Interestingly, Sobuh et al. (2014) found similarities between the gaze behaviours exhibited by intact users of a simulator and amputee subjects - although the task used had relatively few movement phases and no examination of the temporal disruption to gaze was reported. Therefore, future research should examine if these findings transfer to clinical populations. Second, the present study is also potentially limited by the fixed rather counterbalanced order of hand conditions. However, such is the difference in control mechanisms when using the prosthetic hand (compared to the anatomic), that any gains from practicing the task with the anatomic hand would have been irrelevant in facilitating prosthetic hand control. Finally, whilst our gaze shifting measure provided some temporal detail regarding the allocation of gaze during the early part of each task phase, more fine-grained analyses could be explored in future research by quantifying the number of look-ahead and look-back fixations within task phases (Chadwell et al., 2016). Despite this, our relatively simple measure of the temporal allocation of gaze was sensitive enough to be a significant predictor of task performance.

To conclude, the present study clearly shows that the early stages of prosthetic hand use are characterised by a severe breakdown in the spatial and temporal coupling between vision and action in this task requiring fine motor control. While great strides are being made in the technological advancements of prosthesis design and manufacture, it is clear that empirical studies examining the optimal method for teaching users to interact with this technology are still in their infancy. By increasing our understanding of the specific mechanisms behind the disruption to eye-hand coordination we have highlighted key metrics that can be used to determine the effectiveness of any intervention designed to re-establish optimal eye-hand coordination in prosthetic hand users.

Acknowledgments

We would like to thank Bruce Ratray and Tim Verrall (Steeper Ltd) and the technicians at Aintree Hospital, Liverpool, for their assistance with the design and manufacture of the prosthetic hand simulator.

Funding

This research was support by a Royal Society grant (RG140418) that was awarded to GW and SJV.

Reference list

Bouwsema, H., Kyberd, P. J., Hill, W., van der Sluis, C. K., & Bongers, R. M. (2012). Determining skill level in myoelectric prosthesis use with multiple outcome measures. *Journal of Rehabilitation Research and Development*, *49*(9), 1331–1348.

Brand, P. W. (1985). *Clinical mechanics of the hand*. Mosby.

Burnod, Y., Baraduc, P., Battaglia-Mayer, A., Guigon, E., Koechlin, E., Ferraina, S., … Caminiti, R. (1999). Parieto-frontal coding of reaching: an integrated framework. *Experimental Brain Research*, *129*(3), 325–346.

Carrozza, M. C., Micera, S., Massa, B., Zecca, M., Lazzarini, R., Canelli, N., & Dario, P. (2001). The development of a novel biomechatronic hand-ongoing research and preliminary results. In *2001 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2001. Proceedings* (Vol. 1, pp. 249–254 vol.1). https://doi.org/10.1109/AIM.2001.936462

Chadwell, A., Kenney, L. P. J., Thies, S. B. A., Galpin, A. J., & Head, J. S. (2016). The reality of myoelectric prostheses : understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(7). Retrieved from http://dx.doi.org/10.3389/fnbot.2016.00007

Clement, R. G. E., Bugler, K. E., & Oliver, C. W. (2011). Bionic prosthetic hands: A review of present technology and future aspirations. *The Surgeon: Journal of the Royal Colleges of Surgeons of Edinburgh and Ireland*, *9*(6), 336–340. https://doi.org/10.1016/j.surge.2011.06.001

Cohen, H. S. (1999). *Neuroscience for Rehabilitation*. Lippincott Williams & Wilkins.

Cohen, J. (2013). *Statistical Power Analysis for the Behavioral Sciences*. Routledge.

Cordella, F., Ciancio, A. L., Sacchetti, R., Davalli, A., Cutti, A. G., Guglielmelli, E., & Zollo, L. (2016). Literature Review on Needs of Upper Limb Prosthesis Users. *Frontiers in Neuroscience*, *10*. https://doi.org/10.3389/fnins.2016.00209

Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont, Calif.: Brooks/Cole Pub. Co.

Hermens, F., Flin, R., & Ahmed, I. (2013). Eye movements in surgery: A literature review. *Journal of Eye Movement Research*, *6*(4), 1–11.

Hoaglin, D. C., & Iglewicz, B. (1987). Fine-Tuning Some Resistant Rules for Outlier Labeling. *Journal of the American Statistical Association*, *82*(400), 1147–1149. https://doi.org/10.2307/2289392

Jenmalm, P., Dahlstedt, S., & Johansson, R. S. (2000). Visual and Tactile Information About Object-Curvature Control Fingertip Forces and Grasp Kinematics in Human Dexterous Manipulation. *Journal of Neurophysiology*, *84*(6), 2984–2997.

Johansson, R. S., Westling, G., Bäckström, A., & Flanagan, J. R. (2001). Eye-hand coordination in object manipulation. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *21*(17), 6917–6932.

Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience*, *26*(01), 51. https://doi.org/10.1017/S0952523808080899

Land, M., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception*, *28*(11), 1311–1328.

Light, C. M., Chappell, P. H., & Kyberd, P. J. (2002). Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of Physical Medicine and Rehabilitation*, *83*(6), 776–783. https://doi.org/10.1053/apmr.2002.32737

Masters, R., & Maxwell, J. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*(2), 160–183. https://doi.org/10.1080/17509840802287218

Masters, R. S. W., Poolton, J. M., & Maxwell, J. P. (2008). Stable implicit motor processes despite aerobic locomotor fatigue. *Consciousness and Cognition*, *17*(1), 335–338. https://doi.org/10.1016/j.concog.2007.03.009

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2003). The role of working memory in motor learning and performance. *Consciousness and Cognition*, *12*(3), 376–402. https://doi.org/10.1016/S1053-8100(03)00005-9

Miles, C. a. L., Wood, G., Vine, S. J., Vickers, J. N., & Wilson, M. R. (2017). Quiet eye training aids the long-term learning of throwing and catching in children: Preliminary evidence for a predictive control strategy. *European Journal of Sport Science*, *17*(1), 100–108. https://doi.org/10.1080/17461391.2015.1122093

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Pasluosta, C. F., Tims, H., & Chiu, A. W. L. (2009). Slippage Sensory Feedback and Nonlinear Force Control System for a Low-Cost Prosthetic Hand. *American Journal of Biomedical Sciences*, 295–302. https://doi.org/10.5099/aj090400295

Pelz, J. B., & Canosa, R. (2001). Oculomotor behavior and perceptual strategies in complex tasks. *Vision Research*, *41*(25–26), 3587–3596.

Pylatiuk, C., Schulz, S., & Döderlein, L. (2007). Results of an Internet survey of myoelectric prosthetic hand users. *Prosthetics and Orthotics International*, *31*(4), 362–370. https://doi.org/10.1080/03093640601061265

Sailer, U., Flanagan, J. R., & Johansson, R. S. (2005). Eye-hand coordination during learning of a novel visuomotor task. *The Journal of Neuroscience: The Official Journal of the*

Society for Neuroscience, *25*(39), 8833–8842. https://doi.org/10.1523/JNEUROSCI.2658-05.2005

Sobuh, M. M., Kenney, L. P., Galpin, A. J., Thies, S. B., McLaughlin, J., Kulkarni, J., & Kyberd, P. (2014). Visuomotor behaviours when using a myoelectric prosthesis. *Journal of NeuroEngineering and Rehabilitation*, *11*, 72. https://doi.org/10.1186/1743-0003-11-72

Tatler, B. W., Hayhoe, M. M., Land, M. F., & Ballard, D. H. (2011). Eye guidance in natural vision: Reinterpreting salience. *Journal of Vision*, *11*(5), 5–5. https://doi.org/10.1167/11.5.5

van der Meer, A. L., van der Weel, F. R., & Lee, D. N. (1995). The functional significance of arm movements in neonates. *Science (New York, N.Y.)*, *267*(5198), 693–695.

van der Meer, Audrey L. (1997). Keeping the arm in the limelight: Advanced visual control of arm movements in neonates. *European Journal of Paediatric Neurology*, *1*(4), 103–108. https://doi.org/10.1016/S1090-3798(97)80040-2

Vickers, J. N. (2007). *Perception, Cognition, and Decision Training: The Quiet Eye in Action*. Human Kinetics.

Vickers, J. N., & Williams, A. M. (2007). Performing Under Pressure: The Effects of Physiological Arousal, Cognitive Anxiety, and Gaze Control in Biathlon. *Journal of Motor Behavior*, *39*(5), 381–394. https://doi.org/10.3200/JMBR.39.5.381-394

Vine, S. J., Masters, R. S. W., McGrath, J. S., Bright, E., & Wilson, M. R. (2012). Cheating experience: Guiding novices to adopt the gaze strategies of experts expedites the learning of technical laparoscopic skills. *Surgery*, *152*(1), 32–40. https://doi.org/10.1016/j.surg.2012.02.002

Vine, S., Moore, L., Cooke, A., Ring, C., & Wilson, M. (2013). Quiet eye training: A means to implicit motor learning. *International Journal of Sport Psychology*, *44*((4)), 367–386.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences*, *8*(6), 266–272. https://doi.org/10.1016/j.tics.2004.04.002

Williams, M. R., & Walter, W. (2015). Development of a Prototype Over-Actuated Biomimetic Prosthetic Hand. *PLOS ONE*, *10*(3), e0118817. https://doi.org/10.1371/journal.pone.0118817

Wilson, M., McGrath, J., Vine, S., Brewer, J., Defriend, D., & Masters, R. (2010). Psychomotor control in a virtual laparoscopic surgery training environment: gaze control parameters differentiate novices from experts. *Surgical Endoscopy*, *24*(10), 2458–2464. https://doi.org/10.1007/s00464-010-0986-1

Wilson, M. R., Causer, J., & Vickers, J. N. (2015). *Aiming for Excellence*. Routledge Handbooks Online. Retrieved from https://www.routledgehandbooks.com/doi/10.4324/9781315776675.ch3

Wilson, M. R., McGrath, J. S., Vine, S. J., Brewer, J., Defriend, D., & Masters, R. S. W. (2011). Perceptual impairment and psychomotor control in virtual laparoscopic surgery. *Surgical Endoscopy*, *25*(7), 2268–2274. https://doi.org/10.1007/s00464-010-1546-4

Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S. W., Defriend, D., & McGrath, J. S. (2011). Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: a randomized, controlled study. *Surgical Endoscopy*, *25*(12), 3731–3739. https://doi.org/10.1007/s00464-011-1802-2

Wilson, M. R., Vine, S. J., & Wood, G. (2009). The Influence of Anxiety on Visual Attentional Control in Basketball Free Throw Shooting. *Journal of Sport and Exercise Psychology*, *31*(2), 152–168. https://doi.org/10.1123/jsep.31.2.152

Wood, G., Miles, C. A. L., Coyles, G., Alizadehkhaiyat, O., Vine, S. J., Vickers, J. N., & Wilson, M. R. (2017). A randomized controlled trial of a group-based gaze training intervention for children with Developmental Coordination Disorder. *PLOS ONE*, *12*(2), e0171782. https://doi.org/10.1371/journal.pone.0171782

Figures Captions

Fig 1. The prosthetic hand simulator (top left), the simulator being worn (bottom left) and a screenshot from the eye-tracker showing the task environment (right) and the Areas of Interest (AOIs). The magenta crosshair represents the captured pupil in the Eye-vision software and the red cursor (located on the coin) represents the participant's point of gaze.

Fig 2. Action shots taken from the eye-tracker camera for each of the six movement phases, indicating the onset and offset of each phase throughout the coin task. The magenta crosshair represents the captured pupil in the Eye-vision software and the red cursor represents the participant's point of gaze.

Fig 3. Mean (± s.e.m) total percentage of fixations dedicated to each area of interest for each hand condition.

Fig 4. Mean (± s.e.m) target locking score for the anatomic and prosthetic hand conditions across the six movement phases.

Fig 5. Mean (± s.e.m) time to shift gaze for the anatomic and prosthetic hand conditions across the six movement phases. Positive times reflect a gaze shift after completion of a task phase whereas a negative time reflects a gaze shift before a manipulation has been complete.

Fig 6. Complete sequence of gaze allocation and task phase events during a single anatomic (top) and prosthesis (bottom) trial of the coin task. Trials were chosen from participant 7 whose performance times fell closest to the group means. The top row of each hand condition represents the duration of each task phase (B1 = Button press 1, R = Reach, D = Drag, L = Lift and Drop, B2 = Button press 2, H = Hand return). The Button, Coin, Jar, Hand mat, and Other rows indicate when (in relation to task) gaze was fixated on each of these AOIs. Finally, the bottom two rows indicate whether the fixations towards these AOIs were deemed as either hand-focused or target-focused.