RUNNING HEAD: EYE-MOVEMENTS AND IMAGINED MOVEMENT TIME

TITLE: Eye-movements support chronometric imagery performance even when the task is occluded

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Abstract

Mental chronometry has often been used to provide a temporal comparison between executed and imagined movements, with smaller discrepancies indicating more accurate image production and better imagery performance. In this study, we examined the importance of retinal and extra-retinal information in the performance of simple, sequential movements. After physical practice of four activities of daily living (Southampton Hand Assessment Procedure), nineteen participants imagined completing the same tasks with: 1)free eye-movements and visible objects, 2)free eye-movements and no visibility of the objects and 3)constrained eye-movements and visible objects. Results suggested imagery performance was slower/less accurate compared to physical execution, when the eyes were constrained. Conversely, chronometric imagery performance was unaffected with free eye movements, even when task-specific visual information was occluded. This study highlights the crucial role that eye-movements play in the regulation of the temporal aspects of imagery even when retinal information is absent, suggesting that temporal sequencing of imagined actions is largely dependent on extra-retinal information sources.

Keywords: Mental Imagery; Mental Simulation; Mental Chronometry; Gaze; Oculomotor

Introduction

Motor imagery - the active process during which the representation of a specific action is internally reproduced without any overt output (Decety & Grèzes, 1999) - has been shown to be effective at improving motor performance (Smith, Wright, Allsopp & Westhead, 2007; Wright & Smith, 2009). This improvement has been attributed to a shared motor representation between imagery and execution so that the mere imagination of movement can utilise a similar neural network as physical execution (Hardwick, Caspers, Eickhoff, & Swinnen, 2018). This shared representation has been frequently evidenced at the behavioural level by the physical and mental chronometry of movements, where the factors underpinning physically executed movement time correspond with imagined movement time (Decety & Jeannerod, 1995; Malouin, Richards, & Durand, 2012; Roberts, Welsh, & Wakefield, 2019; see Guillot & Collet, 2005 for a review).

The functional role that eye-movements play in image generation and retrieval is well documented. Studies suggest that the generation of a mental image is acted out by the eyes in a process where a mental search of internal memory is accompanied by an oculomotor search of external space (Spivey & Geng, 2001). In explanation, Causer et al., (2013) suggested that during imagery, the object recognition system (occipital areas and ventral stream) are primed causing a pattern of neural reactivation (the visual image) to be generated that is assisted by an oculomotor-based coordinate system. Given this evidence, it is unsurprising that the eye-movements that underpin the execution of object manipulations are somewhat congruent with the eye-movements exhibited during the imagery of these same object manipulations. For instance, Heremans, Helsen and Feys (2008) showed 89% of participants exhibited task-relevant eye-movements during imagery and this was similar (84%) even when participants imaged with their eyes closed (see also, McCormick, Causer & Holmes, 2013 for similar findings). Despite the similarity in oculomotor activity across conditions, there is generally less time devoted to fixating the key target properties during the imagery of visually guided movements (McCormick, Causer & Holmes, 2012), which will inevitably have a negative influence on the temporal aspect of these actions when imagined.

Unsurprisingly, the time course of eye movements has also been shown to support imagery performance (Gueugneau, Crognier & Papaxanthis, 2008; Heremans, Helsen, De Poel, Alaerts, Meyns & Feys, 2009) and, furthermore, the manipulation of information from the visual system impairs the temporal judgment of imagined actions. For example, it has been shown that imagined movement time becomes slower, and thus less accurate, when eye-movements are constrained (Gueugneau et al., 2008) and when the visibility of the surrounding task environment is no longer permitted (Heremans et al., 2009). These findings suggest that both retinal information (e.g., visibility of the environment) and extra-retinal information (e.g., efference copies of motor commands and proprioceptive information from moving the eyes) seem to support chronometric imagery performance. What is not clear is the relative contribution, and relative importance, of each source of information for the production of temporally comparative imagery.

The aim of the present study was therefore to distinguish the contribution of retinal and extra-retinal information for the temporal sequencing of imagery performance. Thus, we had participants execute or imagine a standardised upper-limb movement featuring a number of functional daily targets (e.g., key, zip, handle). The imagery conditions involved free eye-movements with target visibility, free eye-movements with no target visibility and constrained eye-movements with target visibility. Based on previous evidence, we predicted that the imagined movement time would be less accurate (relative to the baseline-executed time) when the eye-movements were constrained regardless of the target visibility.

Materials and Methods

Participants

Nineteen right-handed participants were recruited (male = 8, aged 18-25years). None of the participants had previously undertaken imagery training and all had normal or corrected-to-normal vision. All participants gave written informed consent to take part in the study, which was ethically approved by institutional ethics committee prior to testing.

Measures

Eye-Movements

Eye-movements were measured with a Mobile Eye XG gaze registration system (Applied Science Laboratories, Bedford, MA) that measures eye line of gaze at 30 Hz with respect to eye and scene cameras mounted on a pair of glasses. The system consists of a digital recording device and a laptop (Dell Inspiron 6400, Texas, United States) with Eye-vision software installed (ASL; Bedford, MA).

Chronometric Imagery Performance

Tasks were taken from the Southampton Hand Assessment Procedure (SHAP; Light, Chappell, & Kyberd, 2002), which is an assessment tool to measure hand dexterity. For the purpose of the present study, we used the key turn task (requiring a key to be turned clockwise within a door lock); the horizontal zip task (requiring a zip to opened and fastened from right to left); the door handle task (requiring a door handle to be turned down and up) and then a combination of all the tasks together in the order outlined (Light, 2000). The order remained consistent to ensure that participants had familiarity with each of the discrete tasks before completing these in combination. The SHAP test has been shown to have repeatability on normal subjects and interrater reliability demonstrated at the 95% confidence level (Light et al., 2002).

Procedure

Prior to the experiment, the imagery ability of participants was assessed using the Movement Imagery Questionnaire-3 (MIQ-3; Williams, Cumming, Ntoumanis, Nordin-Bates, Ramsey & Hall, 2012) and handedness was assessed using the Edinburgh Handedness Inventory (Oldfield 1971). Participants who were predominantly right-handed and scored above the mid-point threshold for both visual and kinaesthetic imagery continued with participation in the study. Participants were then calibrated to the eye-tracker and performed the four SHAP tasks. As per the SHAP procedure, participants were required to press a stopwatch that was located to the right of the box (see Figure 1) upon the start and end of each trial, which provided the measure of actual movement time.

After the physical execution trials, participants undertook stimulus and response training based on the work of Lang, Kozak, Miller, Levin and McLean (1980). This involved focusing the participants upon their physiological and behavioural responses to each of the four SHAP tasks (e.g., the touch sensations of the handle or the sub-maximal contractions of the index finger and thumb grasping the key). These responses were used to produce individualised imagery scripts and participants referred to their script at the start of each imagery condition and attempted to incorporate as many as possible during their imagery performance.

Following this training, participants were required to complete the SHAP tasks under three different imagery conditions. The imagery conditions were: (1) free eye-movements and visible target objects (free+visible) where participants were encouraged to move their eyes naturally while the SHAP objects were visible; (2) constrained eye-movements and visible target objects (fixate+visible) where their eyes were fixated on a marked location while the

SHAP objects were visible and (3) free eye-movements and no visibility of the target objects (free+non-visible) were participants were encouraged to move their eyes freely while the SHAP objects were covered by a white screen. Participants completed all conditions in one sitting and these were counterbalanced to reduce the likelihood of fatigue/practice effects from task repetition. Like the physical execution condition, participants were required to press a stopwatch to mark the start and end of the imagined task, which provided a measure of the imagined movement time (e.g., Papaxanthis, Pozzo, Skoura, & Schieppati, 2002; Rozand, Lebon, Papaxanthis & Lepers, 2015; Gueugneau et al., 2008). Each of the four SHAP tasks were executed and imaged over three separate trials.

Data analysis

Gaze data were analysed as a manipulation check in order to ensure compliance with the eye-movement instructions in each of the imagery conditions. Thus, we computed the percentage fixation duration on the key, zip and handle using ASL GazeMap software (Applied Science Laboratories, Bedford, MA) during each of the task conditions by conducting an Areas of Interest (AOI) analysis (Figure 1). Chronometric imagery performance was computed using baseline-referenced comparison scores by subtracting participants' mean execution time from their mean imagery time during each of the imagery conditions (slower imagined movements are indicated by more positive scores). Repeated-measures ANOVAs were used to analyse the data (gaze: task [key, zip, handle, combination] x condition [physical execution, free+visible, free+non-visible, fixate+visible] x location [key, zip, handle]; chronometry: task [key, zip, handle, combination] x condition [free+visible, free+non-visible, fixate+visible]). Effect sizes were reported using partial eta squared statistics, while significant effects featuring more than two means were decomposed using Bonferroni pairwise comparisons. Significance was declared at $p < .05$.

Results

Eye-Movements

A significant task x condition x location interaction was found, $F(3,68) = 103.9$, $p < .001$, $\eta_p^2 = .82$. A repeated-measures ANOVA on each of the tasks indicated that there a was similar condition x location interaction (key: $F(3,68) = 103.9$, $p < .001$, $\eta_p^2 = .82$; zip: $F(2.46,41.86) = 1072.42$, $p < .001$, $\eta_p^2 = .98$; handle: $F(9,153) = 1646.05$, $p < .001$, $\eta_p^2 = .99$; combination: $F(3.42,58.16) = 403.70$, $p < .001$, $\eta_p^2 = .96$). Bonferroni corrected pairwise comparisons revealed that participants in the fixate+visible condition fixated significantly less on the target objects within each of the tasks compared to physical execution of the task (ps < .001), free+visible (ps < .001) and free+non-visible (ps < .001) conditions, which were not significantly different from each other (ps > .5). Thus, it appears that participants followed the initial experimenter instructions surrounding the manipulation of eye-movements. These data are presented in Figure 2.

Chronometric Imagery Performance

A significant task x condition interaction was found, $F(6,108) = 6.42$, $p < .001$, $\eta_p^2 = .26$. Follow-up repeated measures ANOVAs for each task revealed that chronometric imagery performance was not significantly different in the key, $F(1.52, 27.34) = .09$, $p = .913$, $\eta_p^2 = .05$, zip, $F(2, 36) = 1.00$, $p = .91$, $\eta_p^2 = .05$, or handle tasks, $F(2,36) = 1.57$, $p = .222$, $\eta_p^2 = .08$ (see Figure 3). However, a significant difference was found in chronometric imagery performance during the combination task, $F(2, 36) = 5.75$, $p = .007$, $\eta_p^2 = .24$. Post hoc Bonferroni corrected pairwise comparisons revealed that participants' chronometric imagery performance was significantly slower in the fixate+visible condition compared to both free+visible ($p = .034$) and free+non-visible ($p = .046$) conditions, which were not significantly different from each other ($p = 1.00$). These data are presented in Figure 3.

Discussion

Previous research has shown that the chronometry of imagined movements becomes slower, and thus less akin to physical movements, when eye-movements are constrained (Gueugneau et al, 2008) and when the visibility of the task environment is restricted (Heremans et al., 2009). The present study aimed to examine the relative contribution of these retinal and extra-retinal sources in order to understand the information that supports mental chronometry performance during the imagery of movements. The results showed that the time taken during participants' imagery performance for a combination of functional tasks was closer to the physically executed times (as represented by zero in Figure 3) during the free+visible and free+non-visible imagery conditions, while the fixate+visible imagery conditions was slowest and least accurate compared to the other imagery conditions. Put simply, when participants were allowed to freely move their eyes, they generated visual search patterns and imagined movement times that were not significantly different from their physical practice performance – even when task specific visual information was occluded. Conversely, when participants imagined the same task with their vision constrained, the timing of their imagery performance was impaired. Specifically, their temporal error was ~500ms longer compared to their baseline performance.

Firstly, the similar times for execution and imagery attest to a shared representation, where the neural codes that are responsible for execution are correspondingly activated during imagery (Jeannerod, 2001). Moreover, the finding of superior imagery performance when there were free eye movements, which coincided with a similar visual search pattern as physical execution shows how task-specific eye movements support imagery (Heremans et al., 2009; Flanagan & Johansson, 2003; McCormick et al., 2012). This process did not appear to require direct exposure to the target objects themselves following the enhanced imagery performance during the non-visible condition. Taken together, it could be argued that imagery performance relies on accessing a previously stored representation by undertaking a visual search of external space that is specific to the task at-hand (Spivey & Geng, 2001). This extra-retinal information may awaken a visual image of the intended target, as well as a representation that is also responsible for physical execution (see also, Causer et al., 2013).

Notably, the difference between imagery conditions appeared to be restricted to the combined task as there were few differences on the tasks that were performed on their own. In other words, it appeared that the differences unfolded in the more complex sequence task of a longer duration (combined M = 6648 ms vs. key/zip/handle grand M = 3214 ms). In this instance, the differences were primarily related to a more prolonged time within the fixation condition, which would align with previous evidence of an extended imagined compared to executed time for more complex tasks (Calmels et al., 2006; see also, Guillot & Collet, 2005). This feature has been attributed to the recruitment of additional cognitive resources when mentally simulated tasks afford an enhanced level of control or adjustment, which consequently delays the indexing response (i.e., pressing the stopwatch) (Glover & Dixon, 2013; Glover & Baran, 2017). With this in mind, it could be argued that the benefit of eye movements in imagery performance are most abundant when there is some level of difficulty in mentally simulating the task. Future research should examine the relationship between mental chronometry, task duration and eye movements.

A few other explanations of these impairments in mental chronometry when eye-movements were constrained are also worthy of consideration. First, participants could have resorted to using peripheral vision of the task specific targets in order to attempt to maintain chronometry during imagery during the combination task. Interestingly, it has been proposed that targets focused on in the periphery suffer distortions in size and distance (Newsome, 1972) and this may provide an alternative explanation for their impaired imagery performance in this condition. A second explanation may be that participants were susceptible to disruption in goal-directed attentional control and suffered lapses in attention when eye-movements were constrained. It is well established that it is very difficult dissociate attention from eye-movements (Shinoda, Hayhoe, & Shrivastava, 2001) when they are moving in a task specific manner (as in both free eye-movement imagery conditions), but that constraining the eyes increases the susceptibility to lapses in goal directed attention and is synonymous with mind-wandering (Uzzaman & Joordens, 2011). This again could explain why participants over-estimated the movement time when their eyes were constrained during tasks of increased duration.

In conclusion, the study highlights the crucial role of eye-movements in the regulation of the temporal aspects of sequential movements, even when task specific visual information is absent. It suggests that extra-retinal information produced by these eyes allows access to a shared neural network and provides a temporal framework on which imagined actions can be more easily mapped. This provides further evidence of the task specific goal-directed nature of imagery, and specifically the importance of the ocular system in generating effective imagery of complex, sequential actions.

Declaration of interest statement: None

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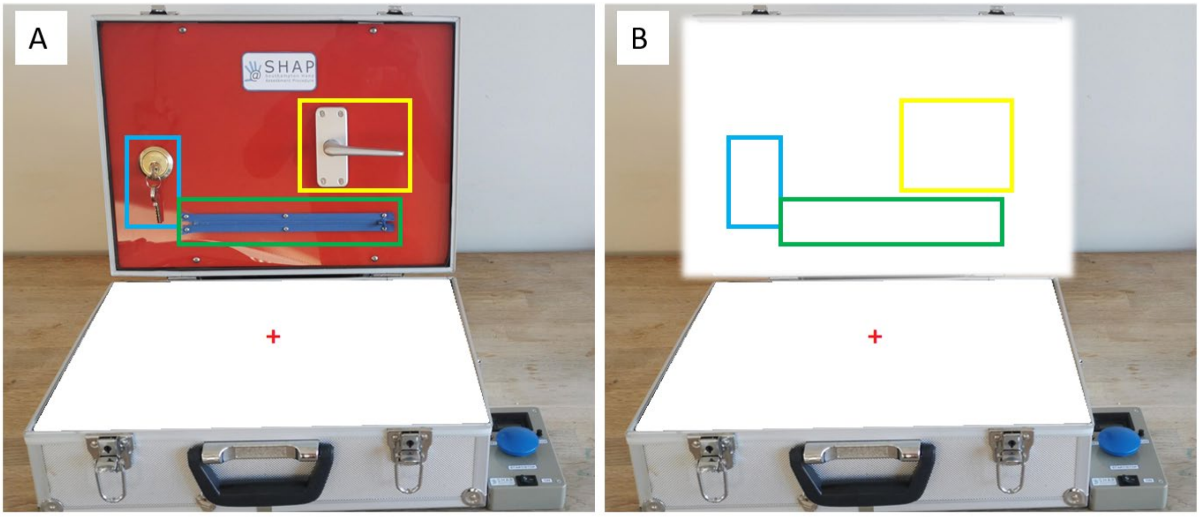
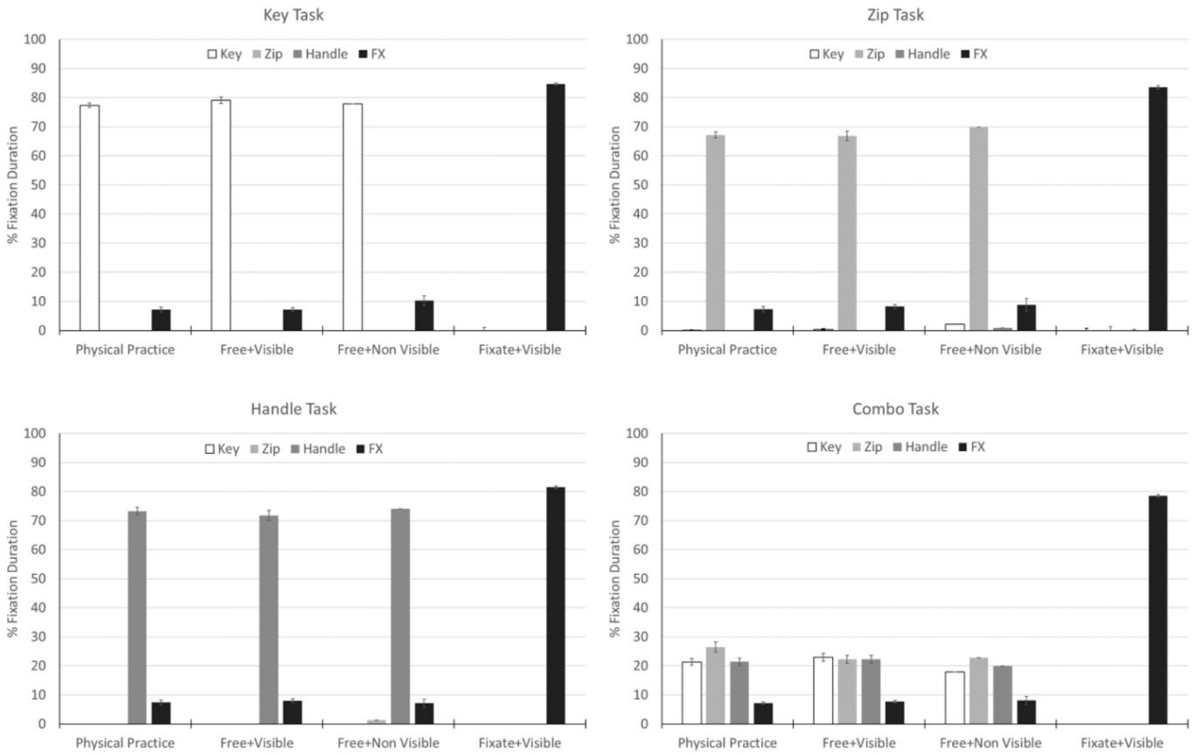
Figure 1. The SHAP task setup and the areas of interest (AOI) used for the gaze analysis. Showing the task display for the free+visible and fixate-visible conditions (A) and the same display for the free+non-visible condition (B). The + in the centre represents the fixation cross where all participants was asked to fixate prior to communing each condition

Figure 2. Eye-movement data showing the allocation of visual attention (% fixation time) in each task across each imagery condition.

Figure 3. Baseline-referenced chronometric imagery performance scores for each imagery condition. A positive score signifies a longer duration compared to baseline and a negative score signifies a shorter time.


A
SHAP
B



Key Task
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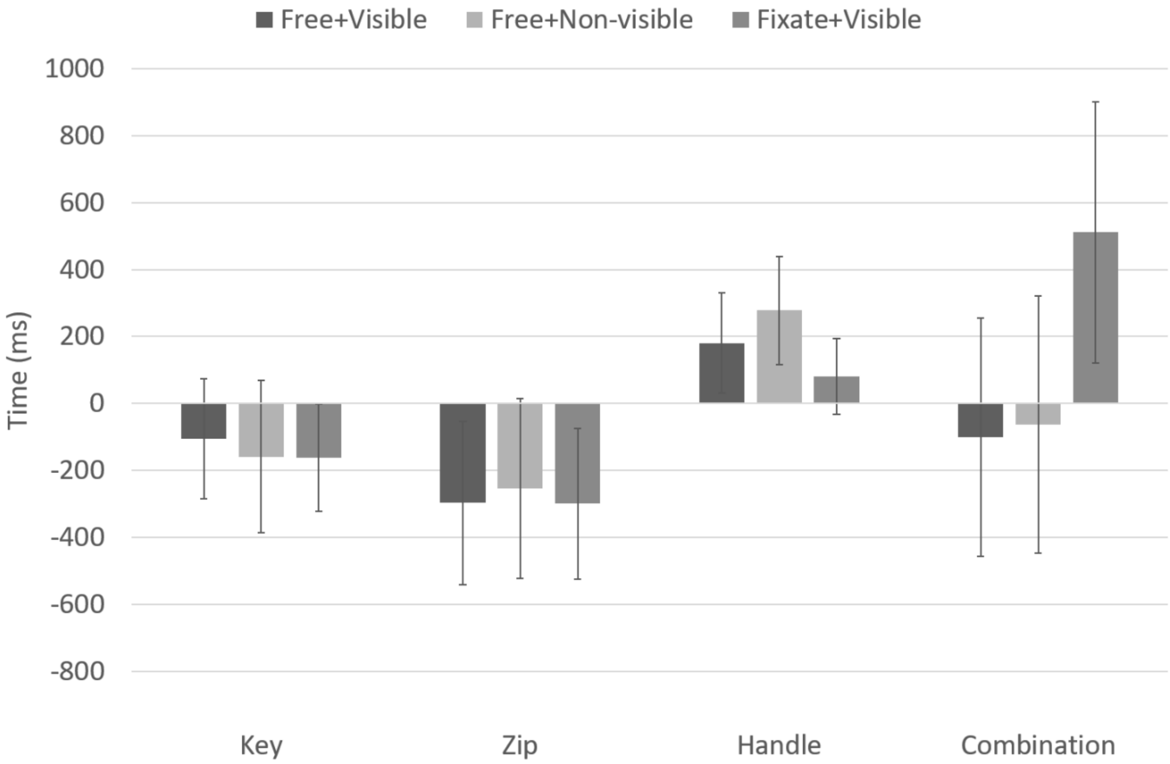
Free+Visible
Free+Non-visible
Fixate+Visible
Time (ms)
1000
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400
200
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-200
-400
-600
-800
Key
Zip
Handle
Combination