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Cognitive plasticity induced by gaze-control technology: Gaze-typing improves performance in the antisaccade task

David Souto[1]*, Olivia Marsh[1], Claire Hutchinson[1], Simon Judge[2,3], Kevin B. Paterson[1]

1 School of Psychology, University of Leicester, Leicester, UK
2 School of Health and Related Research, University of Sheffield, Sheffield, UK
3 Barnsley Hospital, Barnsley

Corresponding author:

David Souto
School of Psychology
University of Leicester
University Rd
Leicester LE1 7RH
d.souto@le.ac.uk

Abstract

The last twenty years has seen the development of gaze-controlled computer interfaces for augmentative communication and other assistive technology applications. In many applications, the user needs to look at symbols on a virtual on-screen keyboard and maintain gaze to make a selection. Executive control is essential to learning to use gaze-control, affecting the uptake of the technology. Specifically, the user of a gaze-controlled interface must suppress looking for its own sake, the so-called “Midas touch” problem. In a pre-registered study (https://osf.io/2mak4), we tested whether gaze-typing performance depends on executive control and whether learning-dependent plasticity leads to improved executive control as measured using the antisaccade task. Forty-two university students were recruited as participants. After five 30-min training sessions, we found shorter antisaccade latencies in a gaze-control compared to a mouse-control group, and similar error-rates. Subjective workload ratings were also similar across groups, suggesting the task in both groups was matched for difficulty. These findings suggest that executive control contributes to gaze-typing performance leading to learning-induced plasticity.

Introduction

The last twenty years has seen the development of advanced gaze-controlled computer interfaces (henceforth gaze-control for short) in the context of augmentative communication and assistive technology applications (Majaranta & Bulling, 2014). Many applications involve selecting keys from a virtual, on-screen, keyboard which allows selection of letters, words, phrases, symbols, or icons allowing computer or environmental control (a.k.a. home automation); or allow direct control of the computer graphical user interface through control of a virtual cursor. A common method of selecting these virtual keys or targets is to maintain gaze on the target for a pre-defined period (termed dwell selection). Here, we focus on gaze-typing and the selection of letters from a virtual on-screen keyboard by dwell time.

For several groups of individuals with severe motor disabilities (Aoki, Hansen, & Itoh, 2009) gaze-control can provide an effective communication tool (Bates, Donegan, Istance, Hansen, & Räihä, 2007). The users of assistive technology to replace or support communication for those with speech impairments, termed augmentative and alternative communication, have a variety of conditions affecting their ability to speak and motor control (Judge, Enderby, Creer, & John, 2017). This includes conditions such as amyotrophic lateral sclerosis (ALS) or cerebral palsy (CP). Interfaces based on gaze interaction take advantage of relatively unimpaired eye movement control in those with ALS (Anderson & MacAskill, 2013) and can be less involved in the unintentional movements that are characteristic of cerebral palsy.

Executive control is at the heart of human ability to generate voluntary behavior, allowing us to activate a goal-appropriate response and suppress automatic responses (Munoz & Everling, 2004). Given that executive function is impaired in many neurodegenerative conditions (Anderson & MacAskill, 2013), knowing how it impacts gaze-typing performance or workload would therefore be of considerable interest in the context of cognitive rehabilitation. This can inform decisions regarding the interface design best suited for assistive technology applications. Furthermore, most studies on gaze-typing focus on using words-per-minute and errors as the main measure of interface effectiveness, leaving aside important issues from the point of view of the user such as the cognitive demands associated with gaze-typing. Here we focus on the role of executive function on performance and workload (including cognitive load) in gaze-typing within a healthy population, compared to an equivalent control task.

Typing skill acquisition

Manual typing with a physical or on-screen keyboard is an important skill to communicate, and it is consequently mastered by many people, achieving typing speeds of 50-100 words per minute (Logan & Crump, 2011). Typing on a keyboard requires the production of a sequence of finger movements in a specific order. Lashley (1951) noted how the simple chaining of stimulus-response associations is unable to account for the speed at which we can generate a correct sequence of movements. Typing has been a task of choice since in investigating serial order (for a review, Logan, 2020; Macneilage, 1964) and automated control (Norman & Shallice, 1986) in motor skill acquisition. Research on typing indicates that several keystrokes are planned at a time (Soechting & Flanders, 1992), starting from the level of words and syllables (Viviani & Laissard, 1996). Skilled performance would rely on the activation of a central motor schema or motor template, representing a keystroke sequence (Viviani & Laissard, 1996), allowing parallel motor planning, while at the same time allowing movement cancellation depending on tactile feedback. Interestingly, Viviani et al (1996) note how the work of Bryan and Harter (1896) on morse coding can be understood in the same way, even though requiring a single movement of the finger. In their study, skill development by individual coders appear to vary in the degree to which they progressed from coding single letters to coding groups of letters and words.

Skill acquisition and cognitive load

A common thread in theories of sensorimotor skill acquisition is that it implies a transition from conscious, declarative, effortful forms of executive control to more automatic and effortless forms of control (Fitts & Posner, 1967; Posner, 1966; Proctor & Dutta, 1995; Shiffrin & Schneider, 1977). More recently, motor actions have been conceptualized as arising from the competition of two control systems working in parallel, each dominant at different stages in skill acquisition (Haith & Krakauer, 2018) (Hardwick, Forrence, Krakauer, & Haith, 2019). One motor control system is slow, effortful and goal-driven and dominates at the beginning of learning, whereas the other is fast, habitual and requires less effort or cognitive load (Haith & Krakauer, 2018). Consistently, after becoming a proficient (manual) typist, paying attention to the hand movement is no longer required and might even hinder performance. Cognitive load corresponds to the extent to which task performance depletes limited mental resources, such as working memory or visual attention capacity. Cognitive load is also an important aspect of instructional theories aimed at improving learning (e.g., mathematics education). This includes the Cognitive Load Theory originally developed by Sweller (2011), and widely applied in the context of human-computer interface usability (Hollender, Hofmann, Deneke, & Schmitz, 2010).

Recent models of motor skill acquisition provide a possible link between faster response selection and a reduced cognitive load with improved skill. The reduction in response times can be seen as a consequence of the “caching” of frequently used computations for rapid use later (Haith & Krakauer, 2018). Here, “caching” is used by analogy with a computer cache, which is a memory reserve allowing for fast retrieval of frequently used information. For instance, when typing the word “poplar”, a typist may rapidly access the sequence of motor movements required to type the syllable “pop” as the computations for these movements have been “cached” as a result of this syllable being produced frequently in the past. This “caching” of computations can therefore speed the selection of keys and overall speed in a manual typing task, while also allowing the typist to allocate cognitive resources to other concurrent tasks. This principle may also apply to gaze-typing, so that the skill acquisition enables the “caching” of computations for specific sequences of eye movements that can speed up item selection and produce faster and less cognitively costly gaze-typing behavior.

Gaze-typing and Midas touch

An important aspect of gaze-control using dwell selection, which departs from what we know about normal typing, is the need to avoid looking for the sake of looking. This is known as “Midas touch” problem (Jacob, 1995). Like King Midas who turned the objects he touched into gold, the user faces the problem of choosing between incompatible action goals. One is to sample sensory information (e.g., touch for the sake of touching) and the other is to act upon the world, such as selecting a virtual object via a “click”. Applied to gaze-control, there is an incompatibility between looking to acquire visual information or looking to select a virtual object via gaze. Executive function may therefore play an important role in learning gaze-control. We hypothesize that learning to type with gaze can in turn affect executive control by inducing behavioral and neural plasticity. The term plasticity was introduced by William James (James, 1890) to suggest the tendency of habits not only to be modifiable but also have some permanence, or put otherwise for the underlying change in organization to keep its shape (Pascual-Leone, Amedi, Fregni, & Merabet, 2005). In that sense, behavioral plasticity can be defined by a modification of behavior induced by learning, and this modification is subtended by more or less permanent changes in functional brain organization (Pascual-Leone et al., 2005; Spierer, Chavan, & Manuel, 2013).

Executive Control

It is likely that the use of technological devices entails behavioral and neural plasticity at different time scales as indicated by behavioral and physiological changes (Classen, Liepert, Wise, Hallett, & Cohen, 1998). For instance, the use of a smartphone (touchscreen), entails use-dependent neural plasticity in sensory areas representing the fingertips (Gindrat, Chytiris, Balerna, Rouiller, & Ghosh, 2015). Adaptive changes can also implicate higher level cognitive skills, such as the executive functions that control the selection of task-relevant actions. In another instance, playing video games and media multitasking (routinely switching between media) are associated with the multitasking performance in standardized tasks (Cardoso-Leite, Green, & Bavelier, 2015).

Eye movements have been used to measure executive function and more specifically our ability to inhibit or suppress automatic behavior, by using the antisaccade task (Hallett, 1978; Hutton, 2008; Munoz & Everling, 2004). In this paradigm, the parameters of saccades directed away from a peripheral target (called antisaccades) are compared with saccades made in the direction of the target (called prosaccades). Antisaccades require an inversion of the visuomotor transformation, which can be achieved by either suppression of the automatic response (the prosaccade) or through a top-down control signal favouring the correct motor command (Hutton, 2008; Kristjánsson, Chen, & Nakayama, 2001). Because top-down control takes time, antisaccades have a longer latency and sometimes fail to activate the correct response before the “reflexive” saccade reaches an execution threshold, generating an error. Behavioral plasticity was also observed after antisaccade training. Antisaccade training has been shown to reduce antisaccade latencies and error-rates after four short daily practice sessions, whereas prosaccade training increases antisaccades error-rates (Dyckman & McDowell, 2005; see also Unsworth, Spillers, Brewer, & McMillan, 2011).

Antisaccade reaction times and error-rates (initial saccade towards the target) have been linked to the integrity of frontal eye fields (FEF), basal ganglia, and superior colliculus (Munoz & Everling, 2004). Experience-dependent plasticity has been shown in FEF; for instance, when monkeys are rewarded after making a saccade towards a red target, certain cells within FEF become selective to red (Bichot, Schall, & Thompson, 1996). Moreover, in a population of hemianopic stroke patients, eye movement training over 4 weeks induced changes in baseline activity in FEF and the supplementary eye field (SEF; Nelles et al., 2009). These changes in FEF neuron’s response could underlie behavioral effects of learning observed in the antisaccade task. Consistently, in humans, antisaccade training results in reduced activation in frontal areas comprising

SEF and FEF, consistent with more efficient top-down control after training (Jamadar, Johnson, Clough, Egan, & Fielding, 2015; Lee et al., 2013).

Gaze-typing and executive control

Our principal aim (see pre-registration: https://osf.io/2mak4) was to test the involvement of executive control in learning to type with the eyes.

Our first hypothesis was that asymptotic typing performance in gaze-control remains poorer than with mouse-control after extensive learning, reflecting intrinsic limitations in using gaze as a control modality and a lack of familiarity with using gaze as a pointing device. For instance, the ability to plan a sequences of eye movements is more limited than the ability to plan a sequence of hand movements, perhaps because eye-movements themselves support hand-movement planning (Diamond, Wolpert, & Flanagan, 2017).

Our main goal was to test the second hypothesis that learning to gaze-type involves executive control by shifting the balance between goal-driven and stimulus driven control of eye movements. We reasoned that if learning induces a change in the executive control of saccades, it will transfer to all goal-driven saccades, thereby improving antisaccade performance. This is consistent with a view of skill acquisition in which frequent neural computations, such as those necessary to associate an appropriate eye movement with a letter to type, can be “cached” for rapid retrieval, improving performance speed and accuracy (Haith & Krakauer, 2018). Those computations may be sufficiently general to benefit antisaccade task performance, which requires a non-habitual mapping as well between a signal and an eye movement. Because anti-saccade performance might improve with repeated testing (i.e., before and after a behavioral intervention), we compared performance across two groups who were training on typing tasks in which a cursor was controlled by either the participant’s eye-gaze or their hand. We predicted a larger improvement in antisaccade performance when the eye controls the cursor, compared to when the hand controls the cursor. Because the eye follows naturally the cursor location (Bieg, Chuang, Fleming, Reiterer, & Bülthoff, 2010) both groups are likely to be well matched in terms of eye movement statistics. Consequently, the main difference between the two groups relates to whether gaze controls the cursor, requiring the generation of task-relevant gaze plans and the suppression of task-irrelevant gaze movements, or gaze follows the cursor but has no direct control over it.

We also hypothesized (third hypothesis) that interindividual differences in executive control predict subjective effort (including cognitive load) in performing the gaze-typing task, indicating the importance of goal-driven control of eye movements in performing the task. More specifically, we expected that better antisaccade performance would correlate with a lower subjective effort in gaze-typing.

To test our hypotheses, we took a different approach compared to the previous literature on gaze-typing. In our experiment, participants produced single words without correction, whereas in earlier research participants typically produced full sentences while allowing corrections (e.g. Majaranta, MacKenzie, Aula, & Räihä, 2006). Our goal in using this paradigm was to characterize skill acquisition in a simple form of gaze-typing task, which focuses on the motoric aspects required to produce a single word. We do not address all our pre-registered hypotheses in the report, but focus here on those hypotheses concerning the transfer of learning to the antisaccade task.

Methods

Participants

There were 42 participants (32 females, aged 18 to 45 years old). Participants were undergraduate or postgraduate students from the University of Leicester's School of Psychology. They were either given £8 per hour or course credit in compensation for their time. The study was approved by the School of Psychology ethics committee, abiding by the guidelines of the Declaration of Helsinki.

We recruited two more participants than our target of 20 per group (ending with 21 in the gaze condition and 21 in the mouse condition) before examining the data, as a preemptive measure to reach our target after drop-outs and to replace participants whose eye movement recordings were noisy. An additional three participants were excluded from analysis because their data was incomplete. One participant did not have a reliable eye movement record (missing data on most trials) in the antisaccade task, while two others failed to complete all sessions. A power analysis (using G*Power 3; Erdfelder, Faul, & Buchner, 1996) showed that with this sample size we could detect with sufficient high power (.86) an interaction between group and testing session (mixed ANOVA) of a moderate effect size (0.25).

Materials

Stimuli were displayed on a HP P1130 CRT screen, with 1280 x 1024 resolution at 85 Hz. Participants' viewing distance was 61 cm. We tracked the right eye during binocular viewing using a video-based eyetracker (Eyelink 1000, SR Research Ltd, Osgoode, Ontario, Canada). We used the Psychophysics toolbox PB-3 on MATLAB to display videos that generated using custom scripts. The Eyelink 1000 has an accuracy of 0.15 deg and a precision of 0.01 deg RMS under ideal conditions (Eyelink, 2009). We used a cutoff accuracy of <.5 deg in our experiment. In the mouse-control group a standard infrared computer mouse and a large gaming mousepad was used to control a cursor.

Data and code availability

The code, including Matlab scripts for implementing the task, R scripts for statistical analyses, and data are available through the Open Science Framework ([link upon acceptance]). The corresponding author welcomes inquiries about how to re-use the interface to fit a specific research purpose.

Experimental design

We used a mixed-design to test within-subjects change in performance in the antisaccade task before and after a typing task and between-subjects performance in gaze- and mouse-typing groups. The nth participant was assigned to a group based on whether it was an odd (gaze-control) or even (mouse-control) participant number. We expected eye movement statistics for gaze and mouse-typing to be well matched, since the eye tends to follow the cursor in computer tasks (Bieg et al., 2010; Ujbanyi, 2018). Groups did not differ in age (gaze-control: 24.8 years old, mouse-control: 23.9 years old), gender composition (both groups had 16 women and 5 men in them).

To investigate whether user experience and usability improved with eye-typing, we used the NASA-TLX scale (Hart & Staveland, 1988), which assesses different dimensions of usability using 6-item rating scale.

We used different tests to control for the influence of language skill on typing. We tested language comprehension with the Mini-NART (McGrory, Austin, Shenkin, Starr, & Deary, 2015; Nelson, 1982). This contains a list of 23 words with irregular spellings (e.g., “aisle”, “labile”) which participants read aloud. Word comprehension was measured using the vocabulary test from the Wechsler Adult Intelligence Scale, 4th edition (Wechsler, 2008). We also tested spelling ability with a list of 20 words taken from the Burt and Tate test (Burt & Tate, 2002; Hersch & Andrews, 2012). Finally, because a typing task requires some memorization of the mapping between letters and spatial locations on the keyboard, we measured spatial memory by using an online adaptation of the Corsi block-tapping test (Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000).

Typing and antisaccade tasks

The typing task is illustrated in Figure 1a-b, showing the virtual keyboard and a trial time-course. Participants typed words drawn out of a high-frequency word list over five sessions either by looking or hovering the cursor with the mouse. Letters were about 0.6 dva wide, had a luminance of 101 cd/m^2 over a gray background (52 cd/m^2). Letters were centered on a grid made of 2.8 x 2.8 dva squares.

The usage of the virtual keyboard in the gaze-control group can be seen in Movie 1 (Movie 1, https://figshare.com/s/4f003b2831cb33507327). We can see how the black cursor changes size depending on the duration that the cursor remains within a “key”, reverting to the initial size after selection (when reaching the dwell time required for selection). To be precise, the cursor had an initial size of 0.14 dva, which increased by a small amount (0.03 deg) every consecutive frame the cursor remained on the key. Once the dwell time required for selection was reached, or the cursor moved to a different key, the key size was reset to its initial value, thereby providing feedback on letter selection.

Whereas most research and practice use fixed dwell times, we adjusted dwell times for selection using an adaptive staircase procedure, starting at a dwell time of 476 ms. Specifically, the dwell time was reduced by 2 frames (23.8 ms) after a correctly written word and up by 2 frames if a typing error was made (the target and produced word did not match). This procedure enabled us to equate difficulty across participants, equate difficulty across control modes, and to fully describe performance by dwell time, since participants’ performance should hover around the same typing error-rate; namely the dwell time for which a correct and incorrect selection become equally likely. Words were of relatively high-frequency (a minimum of 20 occurrences per million words) and were selected from a corpus of English words (http://ucrel.lancs.ac.uk/bncfreq/) to contain no letter repetitions; meaning that each new selection required a movement from the current location on the virtual keyboard. On each trial, target words were selected randomly with replacement from a possible list of 575 words.

Movie 2 (https://figshare.com/s/4f003b2831cb33507327) shows typing in the mouse-control group. The control mode is the same as in the gaze-control group, except that the cursor position is controlled by the mouse.

Finally, the cursor position was smoothed using an iterative exponential filter for x and y coordinates (horizontal and vertical cursor position), such that $x(t) = ax(t) + (1 - a)x(t - 1)$. The "forgetting" parameter a was set to 0.3. It is equivalent to say that the current sample is given a 30% weight compared to the past samples in determining the smoothed cursor location. Without this filter, the cursor would move erratically during gaze-typing due to noise in the eyetracker signal, in strong contrast to the mouse-control group.

The antisaccade task used 4 different blocks of 35 trials, and one training trial per instruction type. Block order was balanced across participants. A block started either with an antisaccade instruction ("look in the direction opposite to the peripheral dot") or a prosaccade instruction ("look at the peripheral dot"). A black (6.7 cd/m^2) fixation dot (0.28 dva) and two placeholders (circles of a diameter of 56 dva at a horizontal eccentricity of 7.5 dva from fixation) were displayed for 500-1500 ms, followed by a dot (.56 dva) randomly allocated to the left or right placeholder location. The target was displayed for 1 second.

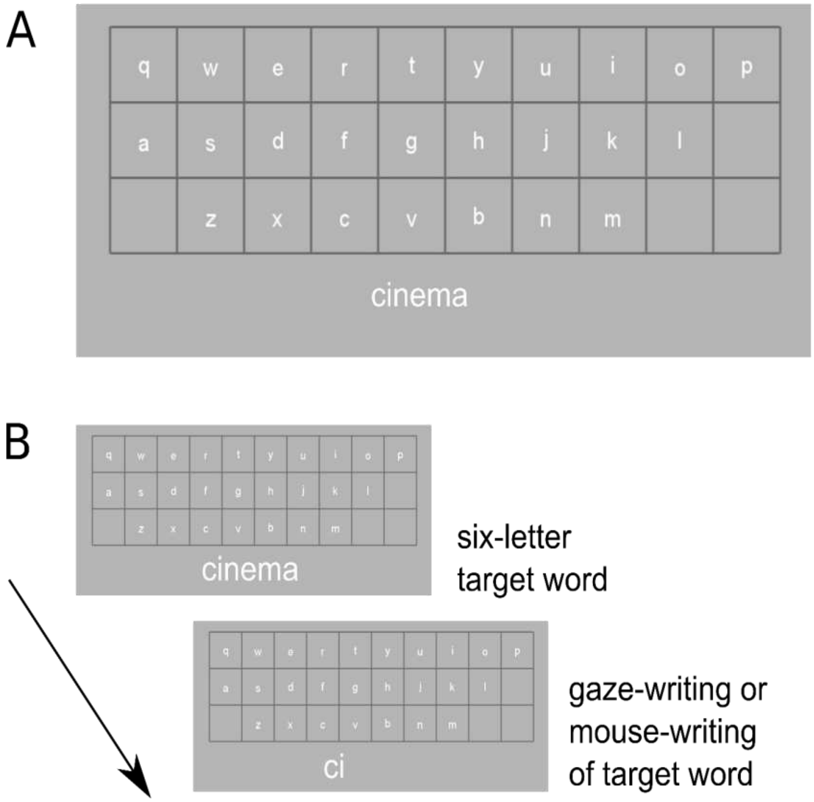

Figure 1. (a) Screenshot (zoomed in) showing the virtual keyboard during the presentation of the target word. We used a familiar QWERTY keyboard layout (UK). The target words and feedback were shown below the keyboard (e.g., the word "cinema"). (b) A trial in the writing task. Words appear beneath the keyboard before writing starts. After pressing the space bar selected letters appear here until six characters have been entered. No correction was allowed.

Experimental Procedure

Experiments took place in a dimly lit room. Participants maintained head position using a chin- and forehead-rest. Participants were then assigned either to the eye-typing or mouse-typing groups. Each participant completed 5 x 30-minute training sessions in which they were required to type a series of 6-letter words, using a virtual keyboard controlled by eye-gaze or a computer mouse. Instructions were to write the target words as accurately and quickly as possible. The antisaccade task was performed before the typing task and again at end of all typing sessions.

Data analysis

We used the *afex* package in R to run a mixed-effects ANOVA testing the effect of test-session and control group on the average saccade latencies and logit-transformed error-rates (e.g. Barton, Pandita, Thakkar, Go, & Manoach, 2008). Per participant and condition, we excluded trials in which latencies exceeded 3 standard deviations above or below the median latency. At most 3 trials in any condition were excluded by this criterion. Other trials were excluded because no latency could be recovered from the eye-movement record. No participant had less than 57 valid trials in any given condition, out of a maximum of 72 trials.

Results

We trained two groups to write with the use of a virtual keyboard; one using gaze to control the cursor and one using a computer mouse. Gaze-control and mouse-control groups had comparable scores on tests of language and spatial skill, shown in Table 1.

Table 1. Mean and +/- SD on tests of spatial memory and language skills in gaze- and mouse-typing groups.

	Corsi Block	WAIS-IV	Spelling	mini-NART
gaze-control (n=21)	6.00 +/-1.34	41.05 +/-6.97	12.50 +/-4.16	13.00 +/-2.73
mouse-control (n=21)	5.59 +/-1.22	41.23 +/-6.62	11.95 +/-4.39	12.14 +/-3.11
Total	5.79 +/-1.28	41.14 +/-6.70	12.21 +/-4.24	12.55 +/-2.93

Better asymptotic performance with mouse-control

We can characterize learning in the typing task can be in terms of a reduction of dwell times across trials, as showing in Figure 2A. By using an adaptive procedure in which dwell time is automatically lowered after a successful trial (i.e., a target word typed without errors) and increased following an error, the dwell-time necessarily hovers around the same typing error-rate in both groups (mouse: .499, C.I.:.497-.501; eye: .510, C.I.: .509-.511). This approach means that the main difference in performance after learning is measured by comparing dwell times, not by comparing typing error-rates. Figure 2 (left panel) shows that dwell time decreased rapidly within the first session for both control modes, but more rapidly in the mouse condition. By comparison with gaze-control, the decrease in dwell time also continued in further sessions. The distribution of dwell times on a given trial is clearly different in mouse and gaze-control groups. The average dwell time at the end of learning, for trials 400 to 450 (Figure 2B) is much longer in the gaze-control condition, with an average of 394 ms [95% C.I.: 346-442] and an average of 233 ms [95% C.I.: 213-253] in the mouse-control group. We can note that variability between people is also larger with gaze-typing, as indicated by confidence intervals that are twice as large compared to the mouse-typing group.

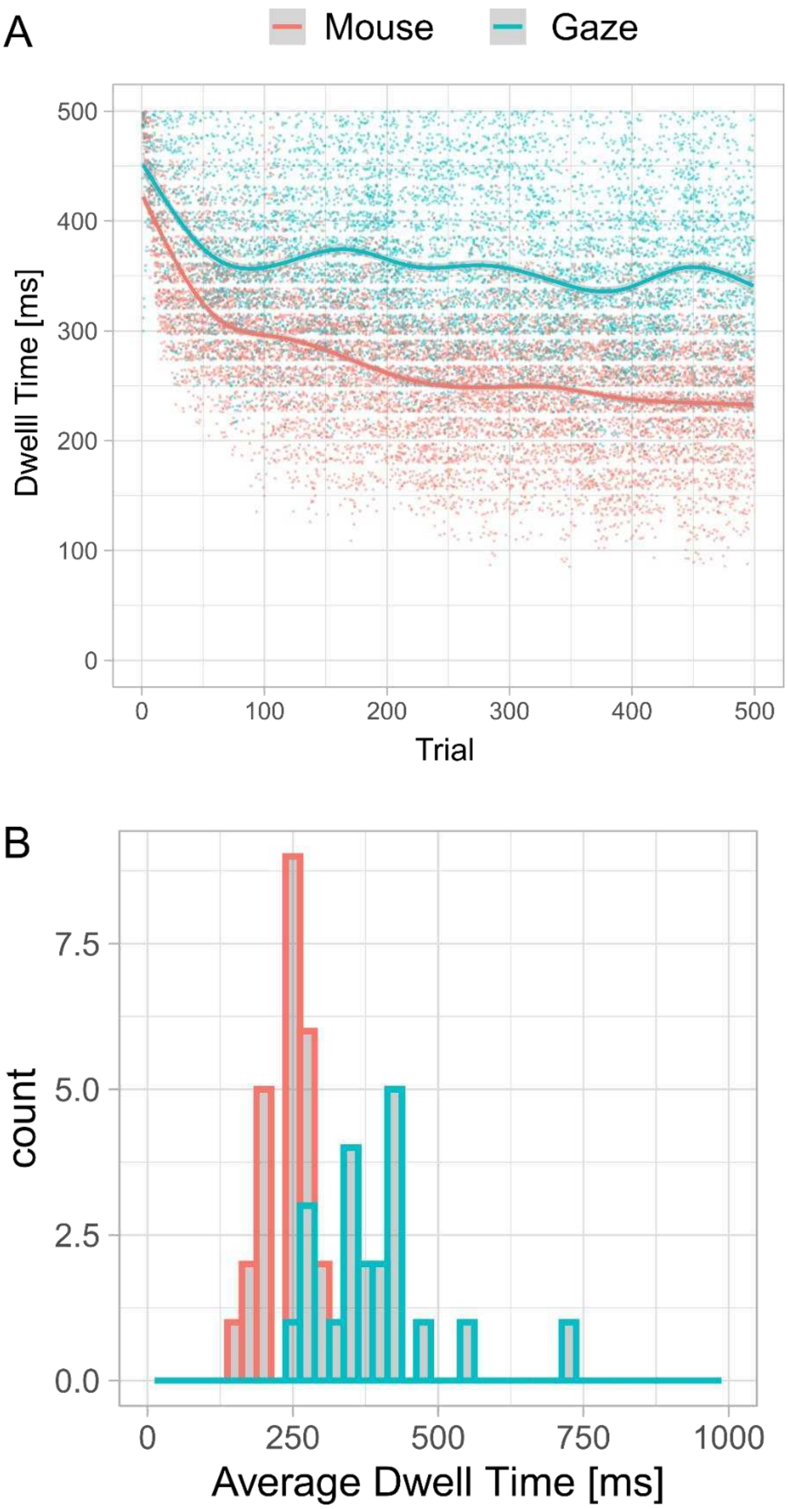

Figure 2. (a) Dwell times across trials. (Note dwell time could exceeded 500 ms for a minority of participants.). The shaded area represents the standard error of the mean. Because dwell time can only be a multiple of a frame duration (11.7 ms), values were jittered vertically for display in the left panel. (b) Histogram for the average dwell time per individual over trials 400-450 in gaze and mouse-writing groups.

Better performance in the antisaccade task in gaze- vs mouse-control

Our main goal was to test whether learning to gaze-type improves antisaccade performance, as indexed by reaction times and directional error-rates (a saccade in the wrong direction). We ran a mixed-effects ANOVA (test session by control group) on latency and logit-transformed error-rates to test this hypothesis.

Figure 4A shows individual and group latencies. A trivial finding is that antisaccades take much longer to be executed compared to prosaccades. With antisaccades, but not prosaccades, we can see speeding up in the post-test that is more pronounced for the gaze-typing group (see Figure 4B). With antisaccades, the analysis confirmed an effect of testing session, F(1,40) = 21.124, p <.001. Participants were faster the second time around (first: 250, second: 237). As predicted, this effect was modulated by control mode, F(1,40) = 4.486, p <.040, with a larger decrease in latencies for the gaze-control group (19 ms) compared to the mouse-control group (7 ms). The main effect of control mode was not statistically significant (p=.25).

Figure 4C shows error-rates for antisaccades and prosaccades. Trivially, error-rates are much higher for antisaccades compared to prosaccades. More important is the fact error-rates are similar across groups, meaning that the interaction between control mode and antisaccade performance is not due to a speed-accuracy trade-off. If anything, the error-rate of antisaccades was lower in the post-test compared to the pre-test in the gaze-control group (13% vs 11%). The mixed-effects ANOVA run on logit-transformed antisaccade errors indicated no main effects of control mode, session, or interaction between factors (all p-values >.38).

Prosaccades latencies were only slightly faster in the second test-session (194 vs 192), and no main effect or interaction was found to be statistically significant (all p*s*>.36). Error-rates were also very similar across test sessions (Figure 4C). The analysis of logit-transformed error-rates indicated no significant effects (all p-values <.29).

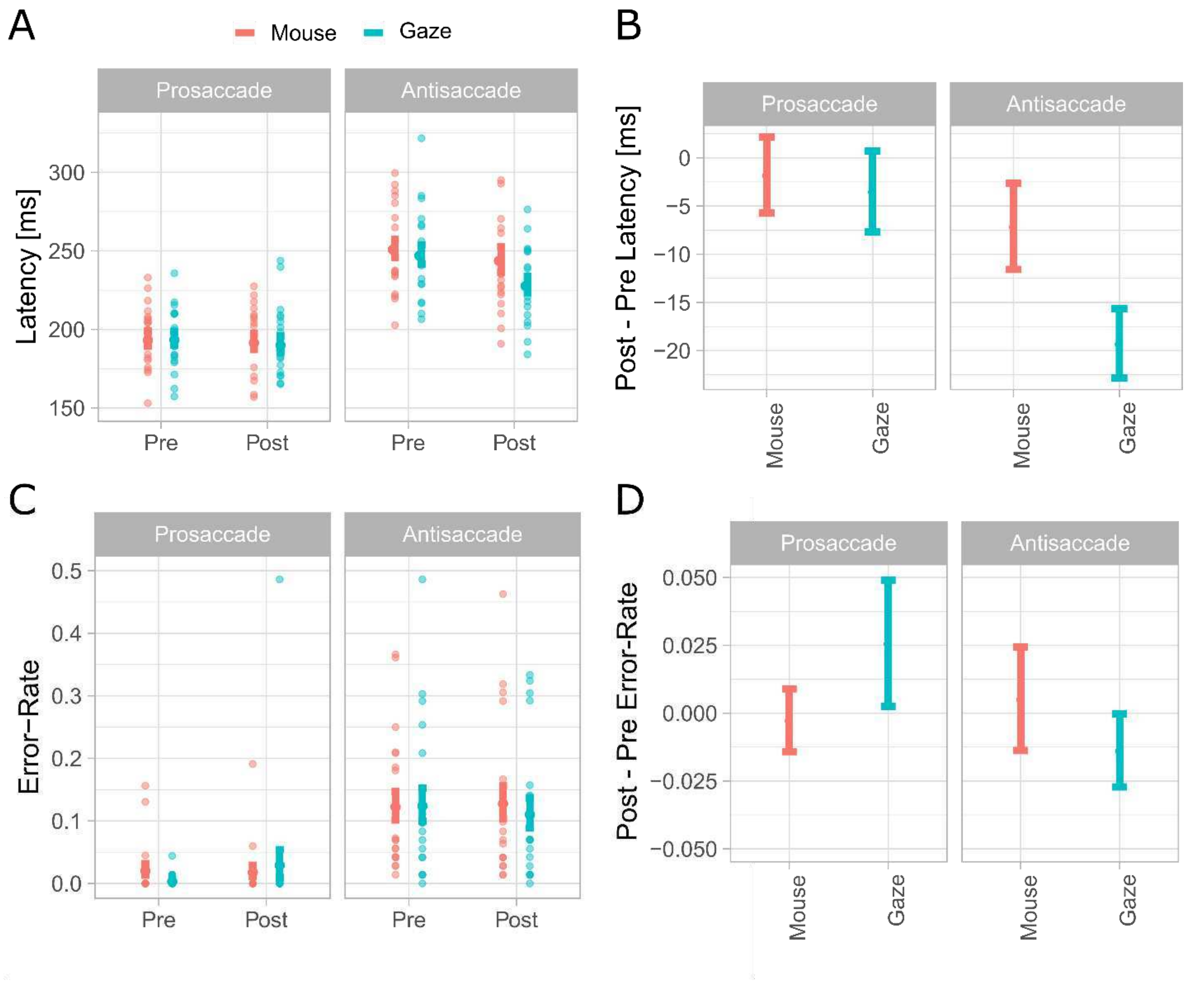

Figure 3. (a-b) The latency in antisaccade and prosaccade trials in pre- and post-tests, depending on control mode. (b) Post-test latencies subtracted to pre-test latencies (c-d) Error-rates in the antisaccade task, that is the proportion of saccades made in the wrong direction. (d) Post-test error-rates subtracted to pre-test error-rates. (a-d) Error bars represent the standard error of the mean.

Usability: Effort and antisaccade performance

We considered whether usability improves with control and whether usability relates to executive control as indicated by the antisaccade task performance. The NASA-TLX (Task Load Index) is a widely used measure of subjective workload that has been applied across domains. Figure 4A breaks down ratings by item, group, and testing session. Ratings were mostly stable across sessions for all items. Effort and mental demand were rated notably higher on the post-session in the gaze-control group. The largest difference between groups is seen in temporal demand, with gaze-typing being perceived as less hurried, which is consistent with higher dwelling times in the gaze-typing group. In both control groups people reported relatively high levels of frustration, although this was also the most variable across people, consistent with a task that generates a high-rate of typing errors (around 50%).

To assess usability differences between the two control groups, we averaged the scores of individual items to produce the so-called Raw-TLX (Hart, 2006). We also calculated a weighted average, resulting from an evaluation of the relative importance of each item, which is the standard way of calculating a global workload with the NASA-TLX. Raw- and Weighted-TLX average scores were remarkably similar across control modes as shown in Figure 4BC, despite clearly faster typing with the mouse.

We tested for an effect of training session (first or last session) or control mode on global workload (Weighted-TLX or Raw-TLX) by running a mixed-effects ANOVA (session x control mode). We found no significant difference between control modes or training session with either workload measure (all p-values > .33).

We tested the hypothesis (third hypothesis in the pre-registration) that interindividual differences in the antisaccade performance relate to subjective workload—whether the task seemed easier for people with better executive control—by correlating antisaccade latency and error-rates with global workload in the first session—that is before learning the typing task. No correlation was significantly different from zero with either workload measure (all p-values < .38).

Another relevant aspect is the subjective relevance of each performance dimension depending on the control group. The NASA-TLX test involves comparing the importance of each dimension by pairs to yield a *factor loading*. Figure 4D shows the average weight given to different dimensions at the start and at the end of training. We can note that effort and mental demand appear relatively more important in the gaze-control than mouse-control group. Effort and mental demand have weights of 16% and 26% for the mouse control group, but 26% and 23% in the gaze-control group. This was consistent with effort and mental demand being rated higher in the last session in the gaze-control group.

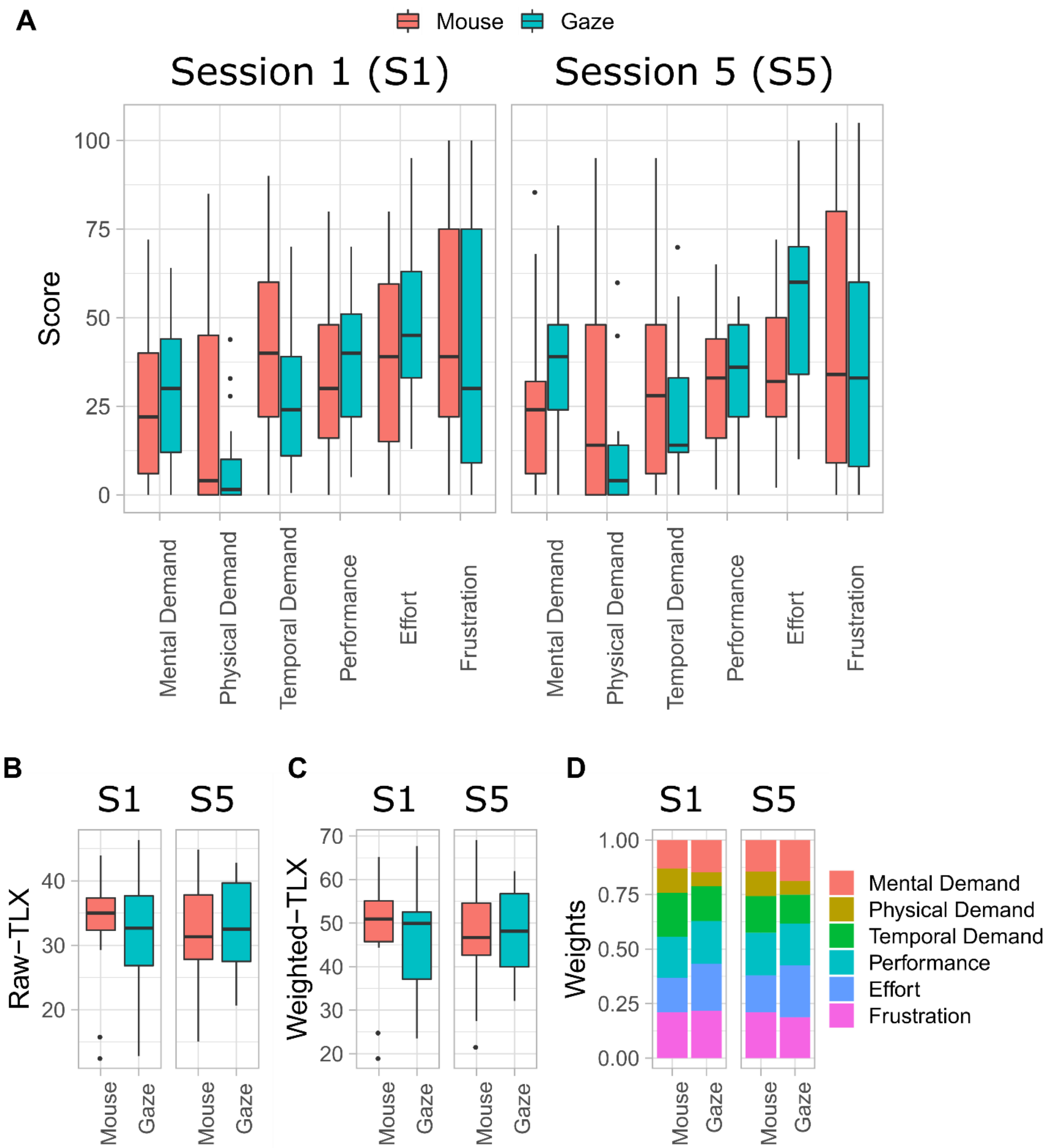

Figure 4. (a-d) Usability ratings in the first (S1) and last (S2) sessions in gaze and mouse-typing groups. (a) NASA-TLX ratings per item. (b) Raw-TLX score (average of ratings). (c) Weighted-TLX (d) Factor loadings, indicating the subjective importance of each item.

Discussion

We tested changes in voluntary eye-movement control using the antisaccade task before and after learning of a gaze- or mouse-typing task. We hypothesized that gaze-typing would induce adaptation of executive control that would transfer to the antisaccade task. The mouse-typing group served as a control where eye movements are likely produced to the same locations but following the cursor rather than causing the cursor movement. We aimed to show whether executive control contributes to solving "Midas touch" problem during gaze-typing, in a relatively simple task requiring participants to write single words containing a fixed number of letters.

A central hypothesis was that antisaccade performance would be better after gaze-typing than it is after mouse-typing. Specifically, we expected greater reduction in the reaction times and directional error-rates of antisaccade trials after gaze-typing than after mouse-typing. We found evidence for the expected reduction in reaction times but not for the directional error-rates, perhaps because they were relatively low at around 12%. Error-rates of up to 25% can be observed in a healthy population, likely depending on instructions to prioritize speed (Hutton & Ettinger, 2006). We also found no evidence of a speed-accuracy trade-off; that is, a speeding up of saccade latencies but increased directional error-rates. Learning to type with gaze transferred to the antisaccade task, resulting in a 5% decrease in reaction times, even though the antisaccade task bears little resemblance to the gaze-typing task, other than both requiring the execution of voluntary saccades. Although we could not confirm a significant difference for prosaccades, the pattern suggests slower prosaccades after training in the gaze-control group. This pattern could be consistent with increased top-down executive control, making the inversion of the visuomotor mapping faster but prosaccades slower, as observed in earlier studies after prosaccade training (Dyckman & McDowell, 2005).

The findings are consistent with rapid experience-dependent plasticity in cortical areas associated with the voluntary control of saccades. A few studies have looked at the effect of gaze-training in generating durable changes (Bichot et al., 1996). Speeded reaction times could result from a change in baseline activity in frontal areas, such as FEF, which show experience-dependent responses after visual field gaze training (Jamadar et al., 2015; Lee et al., 2013; Nelles et al., 2009).

We expected individual differences in antisaccade performance to correlate with subjective effort (including the mental effort item relating to cognitive load) in the gaze-typing task, reflecting the importance of the response selection stage in gaze-typing performance. Consequently, one would also expect task effort to be reduced after training, to reflect an increased automation of the task (Poldrack et al., 2005) and a more efficient suppression of the prepotent response. We found little evidence in favor of these hypotheses. If those differences exist, they were too small to be detected with our design. We traded the ecological validity of the task for a better matching of control modalities. Accordingly, it may be that executive control correlates better with performance in a more naturalistic task, such as writing with the intention of communicating specific information instead of copying words. In that sense our tasks are not as demanding as normal communication by gaze-typing. On the other hand in a normal usage of a gaze-typing system using dwell time (Majaranta & Räihä, 2002), the user would not tolerate a high-rate of typing errors (in our experiment the participant is bound to make frequent typing errors as the dwell time is lowered after a success) and would adjust the dwell time to a level where typing errors are rare. The average 350 ms dwell time in our experiment is close to the 395 ms self-selected dwell-time in Mott et al. (2017) which allowed them to achieve 15 words per minute error-free. Other methods of gaze selection that do not rely on dwell selection have been proposed (Kristensson & Vertanen, 2012) and implemented in commercial systems (e.g. Tobii Dynavox Coummunicator 5, Pittsburg, US). The latter is based on gaze-gestures and uses language models to predict the intended word. Kristensson and Vertanen (2012) suggest that it allows a tripling of writing speed compared to using dwell times, with up to 45 words per minute. While providing a definitive benefit in writing speed, it is not clear whether those systems are more or less taxing on executive function, and it would be of interest to investigate further how they compare in usability and their ability to induce plasticity in saccade executive control.

Mouse and gaze-control

To our knowledge, this is the first study comparing cognitive plasticity and subjective workload resulting from gaze-typing against an appropriate control condition. The mouse is the most widely used selection method with personal computing (Slijper, Richter, Over, Smeets, & Frens, 2009) and therefore we can expect its control to be more efficient at the start. The mouse-control group was not only able to tolerate much shorter dwell times (about 150 ms less) compared to gaze-control, but there was also an indication that learning reached a plateau only in the gaze-control group, suggesting that further improvements may be observed in the mouse control group with more sessions.

There are several fundamental differences between controlling hand movements (mouse) and gaze. One of them is that saccades seem to incur a “gratuitous” delay, called oculomotor procrastination by Carpenter, creating a temporal buffer, meaning that delays at the response selection stage do not necessarily mean a delay in saccade latency (Carpenter, 1981b). We may speculate that oculomotor procrastination, or the tendency for eye movements to be longer than justified by sensory and decisional delays, could explain why gaze-typing would take longer than mouse-typing, without implying a longer saccade programming time. Another reason could be that during manual movements gaze can have a supportive role; we often look ahead of the mouse target. This is likely done to prepare a precise movement (Bieg et al., 2010; Smith, Ho, Ark, & Zhai, 2000). The gaze-control group could, of course, not benefit from this strategy. A possible way to disentangle those two proposals would be to compare mouse typing whilst maintaining a fixed gaze at the center of the keyboard. In this condition, if mouse movements remain faster, it is not (only) because they benefit from visual information acquired through gaze.

Usability

In evaluating a human-computer interface it is essential to go beyond measures of efficiency of performance. For instance, users may prefer slower input methods, if they afford a lower workload. Subjective workloads were relatively stable at the beginning and end of training and there was no indication of a higher workload for gaze-control over mouse-control; either in global measures or looking specifically at effort and frustration related to the control mode. Importantly, and contrary to the intuition that one would need more time to be proficient with gaze-typing (i.e., to use gaze as an effector efficiently) compared to mouse-control, usability scores were similar at the beginning and end of training. However, the lack of fatigue in the use of extra-ocular muscles (Prsa, Dicke, & Thier, 2010), relative to the muscles of the arm, could be factored in to understand subjective ratings. Eye movement fatigue was also not shown during 5 hours of computer use, in a study in which fatigue was operationalized by saccade velocity (Saito, 1992). On the other hand, neither does the operation of a computer mouse generates obvious fatigue, with only measurable levels of physiological fatigue (muscular) after several hours of continuous use (Johnson, Lehman, & Rempel, 1996). Therefore, subjective fatigue in both control conditions is likely to reflect aspects beyond muscular fatigue, such as the amount of effortful control that is required. Anecdotally, some participants in the mouse-control group reported frustration with controlling selection by dwell time, which could conflict with their normal experience of selecting virtual objects by clicking the mouse. Consequently, it could be that operating the mouse by dwell time generated higher workloads compared to its normal function (by pointing and clicking). In that sense, gaze-typing could have reflected higher-workloads compared to a more familiar point-and-click use of the mouse. Overall, typing workloads allow a rough comparison with other computer tasks, which place it in a similar range to the normal use of a computer (30-60 score; Grier, 2015). This is also comparable to subjective workload measured by the NASA-TLX in other gaze-typing experiments (Hayashi & Kishi, 2014).

Generalizability

People who use gaze-control (and gaze-typing) as an assistive technology are not representative of the sample in this study. Those using this technology will have various severe disabilities and will have a different age distribution than our sample made of university students. Before investigating these hypotheses in the gaze-typing population, our approach has been to uncover general principles underlying the acquisition of this novel skill. However, we can ask to which extent our findings generalize across the lifespan and in a population affected by neurodegenerative disease such as ALS or congenital conditions such as CP.

There is evidence that in older adults the capacity to learn (the ability to show improvements in performance) a motor skill is preserved, even though they can take longer and start with a lower performance baseline than younger adults (Ren, Wu, Chan, & Yan, 2013). On the other end, executive function develops slowly over childhood and improves across child development, which translates into faster antisaccade inhibition in adults compared to 10–11-year-olds (Klein & Foerster, 2001). The extent of saccadic adaptation, an indication of plasticity of the visuomotor transformation, was found to be similar between 8 to 20 years old (Salman et al., 2006). The capacity to learn may be similar in tasks that tap into executive function, despite being less mature in children.

It is know that some children with CP can and do use gaze-typing and there has been some investigation into the functional gaze skills of this group which highlights a more complex picture of learning capacity related to gaze control (Griffiths, 2020; Karlsson, Allsop, Dee-Price, & Wallen, 2018). In ALS, there is evidence of a specific deficit in executive function, as indicated by impairments in antisaccade performance with otherwise normal eye movements (Proudfoot et al., 2016; Sharma et al., 2011; Shaunak et al., 1995), but we know of no direct evidence regarding the capacity to learn in relation to executive function.

Outlook

The finding that gaze-typing induces an improvement in the antisaccade task has a practical implication in the context of evaluating changes in cognitive function over time in neurodegenerative conditions such as ALS. The antisaccade task is routinely used to test executive function. The task has a good test-retest reliability (Wöstmann et al., 2013), which makes it a suitable bio-marker of different psychiatric diseases (Hutton & Ettinger, 2006) and a suitable tool for evaluating change in executive control across time. In ALS, eye-movement tests of cognition allow testing at an advanced stage of the disease (Anderson & MacAskill, 2013; Sharma et al., 2011). ALS patients show elevated error-rates and latencies in the antisaccade task (Proudfoot et al., 2016; Shaunak et al., 1995), but show no significant deterioration over time, within a two-year period (Proudfoot et al., 2016). An intriguing question is whether the use of gaze-control technology in this population impacts on the evaluation of executive function. Gaze-control could prove a useful tool both for rehabilitation but also monitoring of oculomotor function, especially since it is used by many patients with neurodegenerative conditions (Bates et al., 2007). Our study suggests that the antisaccade task could be part of a test battery used to evaluate the usability of gaze-control interfaces in relation to workload and performance.

Conclusion

We show that gaze-typing induces plasticity in the executive control of saccades, as suggested by the importance of avoiding looking for the sake of looking, thereby avoiding the “Midas touch” problem. We also show that subjective workload ratings are similar in gaze and mouse-typing, suggesting the mouse-typing control was well-matched for difficulty. This last finding paves the way for understanding specific and general mechanisms involved in gaze interaction.

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