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8 **“Looking-at-nothing” during sequential sensorimotor actions: Long-term**
9 **memory-based eye scanning of remembered target locations**

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1 Abstract

2 Before acting humans saccade to a target object to extract relevant visual information. Even
3 when acting on remembered objects, locations previously occupied by relevant objects are
4 fixated during imagery and memory tasks – a phenomenon called “looking-at-nothing”. While
5 looking-at-nothing was robustly found in tasks encouraging declarative memory built-up,
6 results are mixed in the case of procedural sensorimotor tasks. Eye-guidance to manual targets
7 in complete darkness was observed in a task practiced for days beforehand, while
8 investigations using only a single session did not find fixations to remembered action targets.
9 Here, it is asked whether looking-at-nothing can be found in a single sensorimotor session and
10 thus independent from sleep consolidation, and how it progresses when visual information is
11 repeatedly unavailable. Eye movements were investigated in a computerized version of the
12 trail making test. Participants clicked on numbered circles in ascending sequence. Fifty trials
13 were performed with the same spatial arrangement of 9 visual targets to enable long-term
14 memory consolidation. During 50 consecutive trials, participants had to click the remembered
15 target sequence on an empty screen. Participants scanned the visual targets and also the empty
16 target locations sequentially with their eyes, however, the latter less precise than the former.
17 Over the course of the memory trials, manual and oculomotor sequential target scanning
18 became more similar to the visual trials. Results argue for robust looking-at-nothing during
19 procedural sensorimotor tasks provided that long-term memory information is sufficient.

20

21 **Keywords:** looking-at-nothing, visual attention, eye movements, action control, long-term
22 memory, trail making test

1 **1 Introduction**

2 When interacting with our environment, we use our eyes to extract task-relevant
3 sensory visual information of target objects. However, the eyes are sometimes shifted to
4 remembered targets, although visual information is not available – a phenomenon called
5 looking-at-nothing (Ferreira, Apel, & Henderson, 2008; Johansson, Holsanova, Dewhurst, &
6 Holmqvist, 2011; Richardson, Altmann, Spivey, & Hoover, 2009; Richardson & Spivey,
7 2000). Looking-at-nothing refers to the behavior of saccading to empty locations, e.g., on a
8 screen or behind an occluder where task-related material had been available or is expected to
9 be. This behavior is robustly observed during visual imagery and memory-recall tasks (Brandt &
10 Stark, 1997; Johansson et al., 2011; Johansson, Holsanova, & Holmqvist, 2005, 2006;
11 Johansson & Johansson, 2013; Laeng & Teodorescu, 2002; Mast & Kosslyn, 2002; Noton &
12 Stark, 1971a, 1971b; Spivey & Geng, 2001). It has been hypothesized that saccading to
13 locations that have previously been occupied by to-be-remembered material might facilitate
14 memory encoding and recall (Johansson et al., 2011; Johansson & Johansson, 2013; Laeng &
15 Teodorescu, 2002). As a covert shift of attention obligatorily precedes every gaze shift
16 (Deubel & Schneider, 1996), the facilitated recall might be grounded on attention allocation to
17 the location previously occupied by the to-be-recalled object. In any case, the phenomenon of
18 looking-at-nothing proves that humans can use memory information to direct their gaze to
19 task-relevant locations in space.

20 Imagery and memory-recall tasks encourage explicit or declarative memory encoding,
21 because memory retrieval is explicitly required to solve the task. Therefore, the question
22 arises whether the phenomenon of looking-at-nothing can also be found in tasks that are
23 dominated by implicit procedural memory such as sensorimotor tasks. Fixations to action-
24 target locations in the absence of visual information were indeed found in a well-practiced
25 cup-stacking task (Foerster, Carbone, Koesling, & Schneider, 2012). Participants performed
26 the 14-days trained cup-stacking sequence (speed stacking or sport stacking, see also Foerster

1 et al., 2011) first with normal lighting and afterwards in complete darkness, while gaze was
2 recorded. Even without any visual information, participants saccaded to upcoming hand-target
3 locations slightly before the hands reached the locations. The eye-hand dynamics as well as
4 the sequence of fixated locations, the scanpath, were highly similar between light and dark
5 condition. The results argue that procedural long-term memory (LTM) can indeed be used to
6 direct attention and gaze to target locations when visual information is not available.

7 Contrastingly, Flanagan et al. (2008) found only a loose relationship between eye and
8 hand movements across visual conditions in two sensorimotor tasks. In one experiment,
9 participants pointed to visual versus remembered targets. In another experiment, participants
10 manipulated visual objects or manipulated objects behind a shutter in complete darkness. Both
11 tasks were not practiced beforehand. Pointing target locations were randomly chosen prior to
12 each trial and participants reacted to a specific configuration only once before they had to
13 point from memory, both times in a self-regulated sequence. Similarly, each object-
14 manipulation sequence was repeated only four times with visual information before
15 participants had to act from memory. Thus, procedural memory might have been too fragile to
16 trigger looking-at-nothing in these single-session investigations in which the required motor
17 actions were not practiced much. As it is known that especially procedural learning strongly
18 benefits from sleep consolidation, it is also possible that looking-at-nothing during
19 sensorimotor procedures occurs robustly only after sleep consolidation (Stickgold, 2005;
20 Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). Not only manual but also the
21 corresponding oculomotor trajectory might have been sufficiently consolidated for looking-at-
22 nothing behavior to occur only in multiple day investigations.

23 Here, it is investigated whether looking-at-nothing can robustly be found in a
24 sensorimotor task within a single session, i.e., without intermittent sleep consolidation of the
25 sensorimotor procedure. Crucially, participants started with a longer series of trials with
26 visual information available, allowing to building up procedural memory of a sufficient

1 strength. Afterwards, gaze behavior was investigated over an equally long series of trials
2 without visual information available. Thereby, it can be revealed how robustly participants
3 scan remembered action-target locations with their eyes from LTM when short-term memory
4 has already faded. In this case, looking-at-nothing might be abandoned, modified or
5 intensified provided that action-completion feedback is still available.

6 Eye movements were recorded while participants performed a computerized version of
7 the number connection test or trail making test A (Army Individual Test Battery, 1944;
8 Foerster & Schneider, 2015; Reitan, 1958). In this sequential sensorimotor task, participants
9 had to click as fast as possible on numbered circles in ascending order (here 1 – 9). Visual and
10 procedural LTM encoding was enabled by a 50-trials visual action phase with the same spatial
11 arrangement of nine visual targets. In a consecutive 50-trials memory-based action phase,
12 participants were asked to click at the remembered locations on a blank screen in the same
13 sequence as during the visual phase. Auditory feedback signaled clicking success throughout
14 the experiment. Scanpath analyses were performed to reveal how precisely participants
15 scanned the visual and remembered target locations in sequence over the course of the visual
16 and memory-based action phases.

17

18 **2 Methods**

19

20 ***2.1 Participants***

21 Eleven right-handed students (4 male and 7 female) from Bielefeld University,
22 Germany, participated in the experiment. Participants’ mean age was 25 years. All
23 participants had either normal or corrected-to-normal visual acuity. All were naïve with
24 respect to the purpose of the study, gave informed consent, and were paid for their
25 participation. The study was conducted in accordance with the Code of Ethics of the World
26 Medical Association (Declaration of Helsinki).

1

2 **2.2 Apparatus and Stimuli**

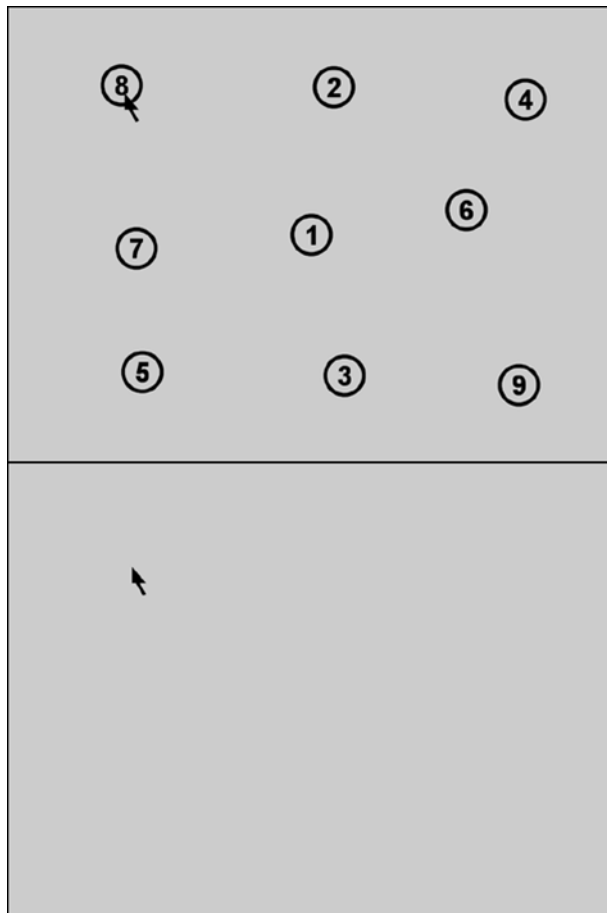
3 The experiment was controlled by the Experiment Builder software (SR Research,
4 Ontario, Canada) on a Dell Optiplex 755 computer. The stimuli were displayed on a 19-in.
5 CRT monitor (ViewSonic Graphics Series G90fB) with a refresh rate of 100 Hz and a
6 resolution of 1,024 x 768 pixels controlled by an ATI Radeon HD 2400 Pro graphics card.
7 The computer mouse and keyboard as well as an extra-large mouse pad (88 x 32 cm) were
8 used. Each participant’s right gaze position was recorded by an EyeLink 1000 tower system
9 (SR Research). The eye tracker’s sampling rate was 1,000 Hz, and participants’ viewing
10 distance was fixed at 71 cm with a chin and forehead rest throughout the experiment. The
11 cursor position was recorded with the monitor’s sampling rate of 100 Hz. Color and
12 luminance were measured at the screen center in CIE Lxy coordinates using an X-Rite i1 Pro
13 spectrophotometer.

14 All stimuli were black ($L = 0.3 \text{ cd/m}^2$, $x = .32$, $y = .33$) and displayed on a gray
15 background ($L = 78.9 \text{ cd/m}^2$, $x = .29$, $y = .30$). The mouse cursor was an upwards pointing
16 arrow of approximately .68 degrees of visual angle ($^{\circ}\text{v.a.}$) width and 1.69°v.a. height. The
17 target stimuli consisted of 9 numbers (Arial, font style bold, font size 35), each surrounded by
18 an unfilled circle (2.04°v.a. diameter, line width 6). The first circle was located in the center
19 of the screen. The spatial distribution of the other 8 circles was randomly generated with the
20 prerequisite that each outer field of an imagined 3 by 3 grid contained one circle and circles
21 had a minimal distance of 2.04°v.a. to each other (from border to border) as well as to the
22 screen border. The minimal distance between the nearest two circles 5 and 7 happened to be
23 5.93°v.a. in the generated display (from center to center). The same spatial configuration was
24 used throughout the entire experiment (Figure 1).

25

1 **2.3 Procedure**

2 The experiment was divided into a first visual action phase with numbered circles on
3 the screen and a consecutive memory-based action phase with a blank screen. Each phase
4 started with a written instruction on the screen followed by a 9-point calibration and
5 validation procedure. Only calibrations with averaged validation accuracy below 1.0° v.a.
6 were accepted. In the visual phase, participants had to click as fast as possible in ascending
7 order on the 9 numbered circles presented on the screen (Figure 1, top). Participants were
8 informed that the configuration of target stimuli stayed the same throughout the whole
9 experiment. An example trial preceded the visual phase. In the subsequent memory phase,
10 only the mouse cursor was displayed on the grey background (Figure 1, bottom), and
11 participants were instructed to click as fast as possible on the locations that were previously
12 occupied by the numbered circles in the same sequence as before. A click was counted as
13 correct, if the mouse cursor was within a diameter of 3.06° v.a. around the current target's
14 center. A correct click was followed by a high-pitched tone. An incorrect click was followed
15 by a low-pitched tone. After all 9 circles were clicked on in the right order trial completion
16 time was displayed on the screen. Each trial was preceded by a central fixation on a black ring
17 ($.45^{\circ}$ v.a. outer size and $.11^{\circ}$ v.a. inner size). The visual phase as well as the consecutive
18 memory phase consisted of 5 blocks à 10 trials, adding up to 100 trials in total. A block
19 information display separated each block. Participants could start each block and trial by
20 pressing the space bar. Participants were allowed to take self-paced breaks in-between blocks
21 and trials. All participants completed the experiment within 40 minutes. The participant with
22 the fastest time in each phase earned 6 €extra.



1
2 Figure 1. Displays during sequential clicking in the visual (top) and memory (bottom) phase
3 of the experiment.
4

5 **2.4 Analysis**

6 The SR Research Data Viewer software’s implemented algorithm was used to detect
7 fixations, saccades, and blinks (velocity threshold of 30°v.a./s and acceleration threshold of
8 $8,000^{\circ}\text{v.a./s}^2$). The following variables were analyzed as dependent variables: Trial
9 completion time, number of clicking errors, number of fixations, distance of fixations and
10 clicks to the current target, eye-hand spans, and scanpath similarity. The eye-hand time span
11 refers to the time interval between a fixation at a specific target and the corresponding action
12 – in this case a click – to the target (cf. Butsch, 1920; Furneaux & Land, 1999; Sailer, Eggert,
13 Ditterich, & Straube, 2000). The eye-hand unit span refers to the number of actions completed
14 in between a fixation at a specific target and the corresponding action – in this case a click –
15 to the target (cf. Foerster et al., 2011, 2012). The eye-hand target distance span indicates

1 whether the eye or the cursor is nearer to the current target. It is calculated by subtracting for
2 each 100 Hz sample the distance of the eye sample position (down-sampled to 100 Hz by
3 averaging the eye position) to the current target’s center from the distance of the cursor
4 position (measured with 100 Hz) to the current target’s center (cursor-target distance minus
5 eye-target distance). Therefore, the eye-hand spans reveal how far ahead the eyes are with
6 respect to the hand within an action sequence. Positive eye-hand spans indicate that the eye is
7 anticipatorily guiding the manual action while negative eye-hand spans indicate that the eye is
8 following the manual action. Scanpath comparisons were performed using FuncSim (Foerster
9 & Schneider, 2013a, 2013b) and MultiMatch (Dewhurst et al., 2012; Jarodzka, Holmqvist, &
10 Nyström, 2010). These methods will be explained in the Results section. Violations of
11 sphericity were corrected using the Greenhouse-Geisser ϵ (uncorrected degrees of freedom are
12 reported to facilitate reading). A chance level of .05 was applied. Data processing and
13 aggregation were performed using Matlab R2013b and Microsoft Excel 2010. Statistical
14 analyses were conducted with IBM SPSS Statistics 22.

15

16 **3 Results**

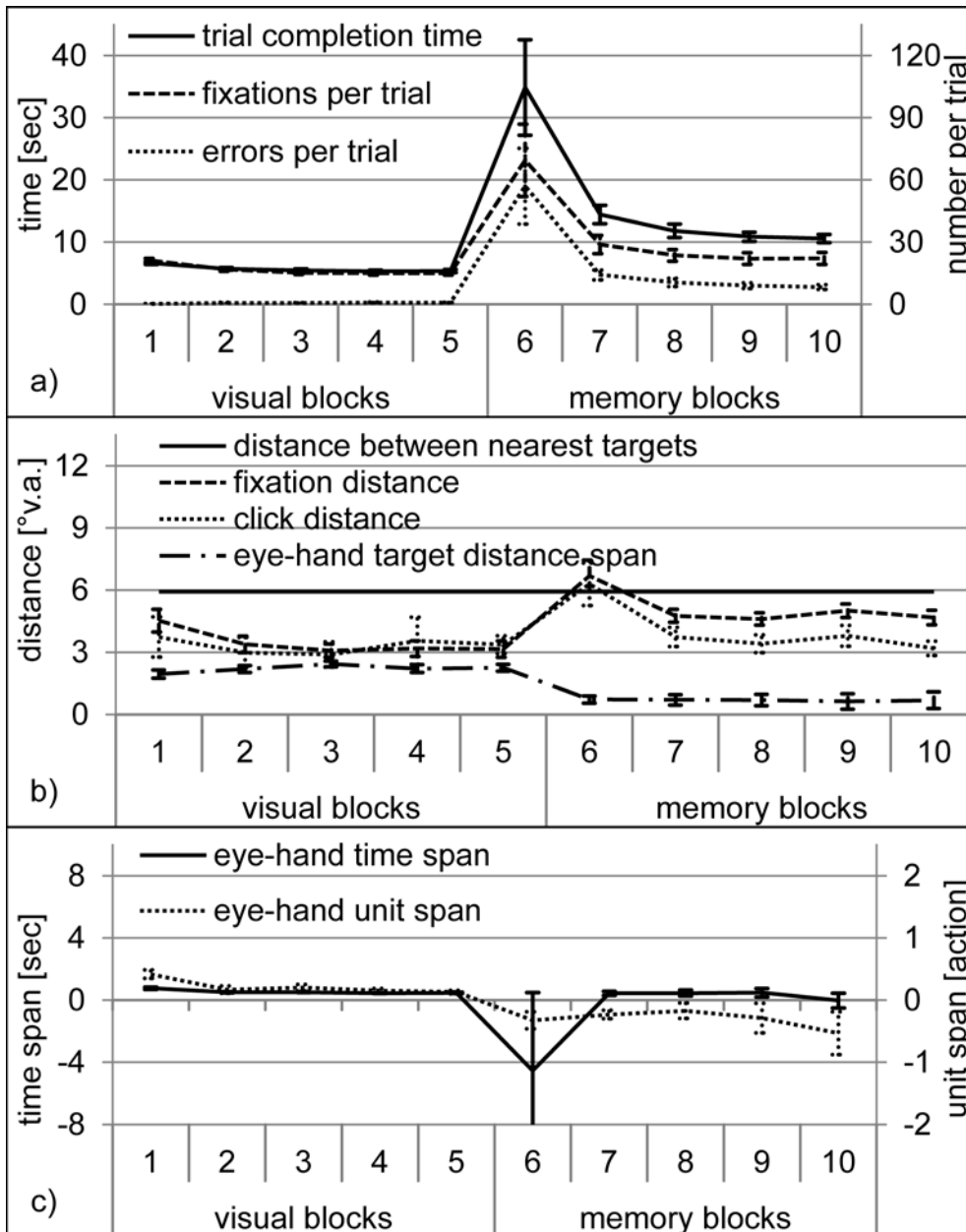
17 The Result section is divided into three parts. In the first part, manual performance and
18 gaze control during the last visual block (block 5) is compared to the first memory block
19 (block 6). The second part provides an analysis of the development of manual and gaze
20 measures when visual information is repeatedly not available. Third, it is investigated whether
21 visually marked as well as remembered action target locations are scanned sequentially with
22 the eyes.

23

24 ***3.1 Performance and gaze patterns with visual versus remembered action targets***

25 To reveal the effects of the lack of visual information, click performance and gaze
26 patterns of the last visual block (block 5) were compared to the first memory block (block 6).

1 Trial completion time, number of clicking errors, number of fixations, and the distance of
2 fixations and clicks to the current target increased significantly as soon as visual information
3 was no longer available and the eye-hand unit span and the eye-hand target distance span
4 decreased significantly (Figure 2; time: $t(10)=3.82$, $SE=7.74$, $p<.01$; number of clicking
5 errors: $t(10)=3.04$, $SE=18.45$, $p<.05$; number of fixations: $t(10)=3.15$, $SE=17.28$, $p<.05$;
6 fixation distance: $t(10)=4.93$, $SE=.72$, $p<.001$; click distance: $t(10)=2.66$, $SE=.82$, $p<.05$; eye-
7 hand unit span: $t(10)=3.10$, $SE=.13$, $p<.05$; eye-hand target distance span: $t(10)=10.21$,
8 $SE=.15$, $p<.001$). The eye-hand unit span decreased from positive to negative values, while
9 the eye-hand target distance span remained positive. The eye-hand time span was not
10 significantly different between the visual and the memory phase ($t(10)=.99$, $SE=4.56$, $p=.34$)
11 due to a high amount of variability, although its average decreased from positive to negative
12 values (Figure 2). Thus, performance dropped when visual information was no longer
13 available and eye movements were less related to the action target locations. During the visual
14 phase, fixations mainly landed at the current action target (eye-hand unit span of 0) or at
15 positions becoming targets even later resulting in a slightly positive eye-hand unit span of .13.
16 The amount of fixations landing at completed target locations increased when acting on
17 remembered target locations, indicated by a slightly negative eye-hand unit span of -.32.
18 Nevertheless, the eye was on average nearer to the current target than the cursor was (positive
19 eye-hand target distance span), even though with a smaller distance between eye and cursor
20 than during the last visual block.



1
2 Figure 2. a) Trial completion times in seconds (solid line and left y-axis) as well as numbers
3 of fixations (dashed line) and clicking errors (dotted line) in number per trial (right y-axis)
4 across all blocks. b) Distance of fixations (dashed line) and clicks (dotted line) to the current
5 target as well as the eye-hand target distance span (dotdashed) in °v.a. across all block. The
6 solid line displays the distance between the nearest two targets (5 and 7) which was 5.93°v.a.
7 c) Eye-hand time span (solid line and left y-axis) in milliseconds and eye-hand unit span
8 (dotted line and right y-axis) in number of actions across all blocks. Error bars represent
9 standard errors of the mean.

10

11 3.2 Performance and gaze patterns when visual targets are repeatedly unavailable

12 When visual information was repeatedly not available, performance and gaze values
13 changed significantly in direction to the visual-phase values as indicated by significant block
14 effects and significant linear trends across the memory blocks by the corresponding

1 ANOVAs. (Figure 2; time: $F(4,40)=9.00$, $\varepsilon=.26$, $p<.05$, $\eta_p^2=.47$, linear trend $p<.01$; number
 2 of clicking errors: $F(4,40)=6.39$, $\varepsilon=.26$, $p<.05$, $\eta_p^2=.39$, linear trend $p<.05$; number of
 3 fixations: $F(4,40)=7.38$, $\varepsilon=.26$, $p<.05$, $\eta_p^2=.43$, linear trend $p<.05$; fixation distance:
 4 $F(4,40)=6.86$, $\varepsilon=.40$, $p<.05$, $\eta_p^2=.41$, linear trend $p<.05$; click distance: $F(4,40)=7.37$, $\varepsilon=.37$,
 5 $p<.05$, $\eta_p^2=.42$, linear trend $p<.05$). In the first memory block (block 6), the distance of
 6 fixations and clicks to the current target was not significantly different from the distance of
 7 5.93° v.a. between the nearest two targets (fixation: $t(10)=1.00$, $SE=.43$, $p=.34$ and clicks:
 8 $t(10)=.35$, $SE=.51$, $p=.73$). Already during the second memory block (block 7), fixations and
 9 clicks landed significantly nearer to the current target than to any other target (fixation:
 10 $t(10)=3.75$, $SE=.25$, $p<.01$ and clicks: $t(10)=4.76$, $SE=.39$, $p<.001$, tested against the distance
 11 of 5.93° v.a. between the nearest two targets). Thus, clicking performance approached a
 12 normal level and eye movements were again related to the current action target locations
 13 when participants were familiarized with the memory-clicking task. However, the eye-hand
 14 unit span remained slightly negative throughout memory-based acting and did not change
 15 significantly over the course of the memory phase ($F(4,40)=.87$, $\varepsilon=.35$, $p=.40$, $\eta_p^2=.08$).
 16 Numerically, it even decreased further. Thus, the eye-hand unit span either remained its
 17 dissimilarity to the visual phase over the course of the memory phase. The eye-hand time span
 18 and the eye-hand target distance span did not change significantly over the course of the
 19 memory phase (eye-hand time span: $F(4,40)=.94$, $\varepsilon=.25$, $p=.36$, $\eta_p^2=.09$; eye-hand target
 20 distance span: $F(4,40)=.06$, $\varepsilon=.47$, $p=.94$, $\eta_p^2=.01$).

21

22 ***3.3 Sequential scanning of visual and remembered action target locations***

23 How similar did participants scan the target locations in sequence with and without
 24 seeing the targets on the screen? Scanpath similarity, i.e., the similarity of fixation location
 25 sequences was calculated using two multi-dimensional scanpath-similarity methods. The first

1 method is MultiMatch (Dewhurst et al., 2012; Jarodzka et al., 2010), a vector-based method
2 that calculates separate sequence similarity scores for the dimensions vector, location,
3 duration, length, and direction. Scores are normalized between 0 (no similarity) and 1 (perfect
4 similarity). The second method is FuncSim (Foerster & Schneider, 2013a, 2013b), a
5 functional sequencing method that is adapted to compute ocular scanpath similarity in
6 sequential motor actions. It calculates difference scores for the dimensions location, duration,
7 length, and direction by aligning the fixations within the compared paths based on the
8 performed sub-actions. In a first step, fixations belonging to the same sub-action are averaged
9 (method ‘*average*’ in Foerster & Schneider, 2013b). In a second step, location, duration,
10 length, and direction differences are calculated within corresponding sub-actions of two
11 scanpaths. With respect to the clicking task, fixations performed after the click on the last
12 target until the click on the current target belong to the same sub-action. In addition, FuncSim
13 calculates scanpath difference scores for each dimension between one of the scanpaths and its
14 scrambled derivative. These scores serve as random baseline difference scores. The
15 scrambling procedure assigns the fixations performed during a sub-action to another randomly
16 chosen sub-action. In this way, fixations are shuffled randomly around as if the click-action
17 sequence would have been different. As the scrambled scanpath consists of actually observed
18 fixations, its comparison to the scanpath in the correct order constitutes a highly conservative
19 random baseline difference score. MultiMatch and FuncSim provide Matlab toolboxes
20 (download links: http://wiki.humlab.lu.se/dokuwiki/doku.php?id=public:useful_links and
21 <http://www.uni-bielefeld.de/psychologie/abteilung/arbeitsseinheiten/01/Research/FuncSim>)
22 which were used for the following analyses.

23 As scanpaths can only be compared pairwise, for each participant all 10 trials of the
24 last visual block (block 5 as reference block) were individually compared to all 10 trials of
25 each of the five memory blocks, resulting in 100 comparisons per block. For random baseline
26 calculation, the last visual block (reference block 5) was used. Each of the 10 trials of the last

1 visual block (block 5) was compared to 10 randomly-chosen sequence-scrambled derivatives,
2 resulting in 100 random baseline comparisons. The same scrambled scanpath comparisons
3 were used for FuncSim and MultiMatch. Only the values of the dimension location are
4 reported here, because the research question was whether visually marked and empty target
5 locations were scanned in a similar sequence. Paired *t*-tests were used to test whether the
6 scanpaths of the last visual block (block 5) were more similar to their own scrambled
7 derivatives or to the memory-based scanpaths of blocks 6-10. The FuncSim location
8 difference scores were additionally compared to the nearest distance of two target locations in
9 the display (5.93° v.a.) and to the click acceptance region (3.06° v.a.) via one-sample *t*-tests.

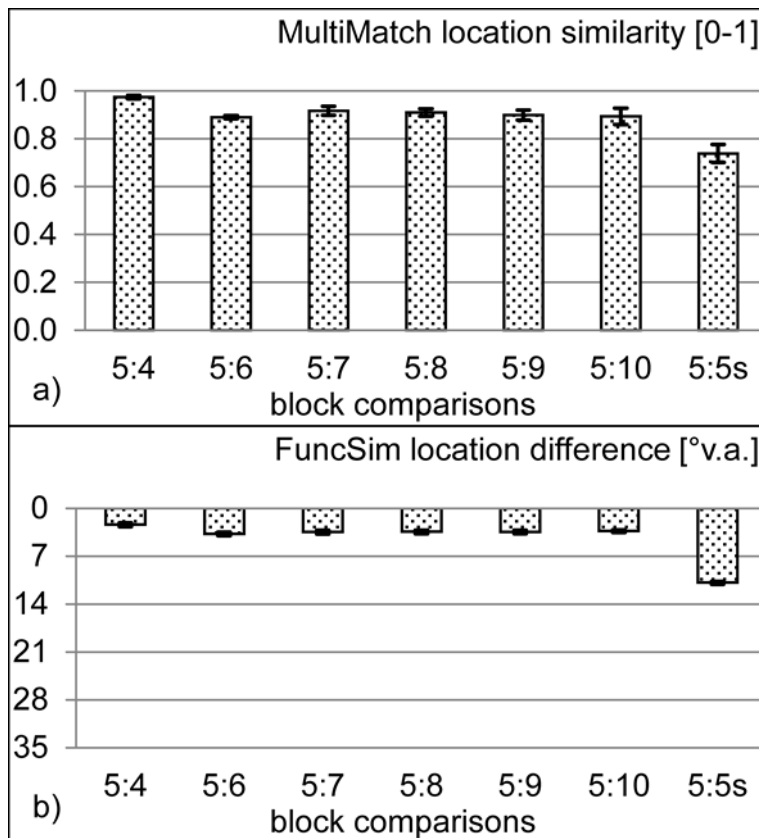
10 Mean MultiMatch location sequence similarities between the last visual block (block
11 5) and the memory blocks 6-10 ranged from .89 to .92 indicating high scanpath similarities
12 between the visual and the memory phase (Table 1 and Figure 3). These similarity scores
13 across the visual and the memory phase were not significantly different from each other
14 ($F(4,40)=.56$, $\varepsilon=.47$, $p=.57$, $\eta_p^2=.47$), indicating that the last visual block (block 5) was not
15 more or less similar to specific memory blocks. Importantly, all location sequence similarities
16 were significantly higher than the random baseline similarities (all $ps<.01$).

17 Mean FuncSim location sequence differences between the last visual block (block 5)
18 and the memory blocks 6-10 ranged from 3.34 to 3.76° v.a. indicating likewise high scanpath
19 similarities between the visual and the memory phase (Table 1 and Figure 4). These
20 difference scores across the visual and the memory phase were not significantly different from
21 each other ($F(4,40)=2.29$, $\varepsilon=.54$, $p=.12$, $\eta_p^2=.19$), indicating that the last visual block (block
22 5) was not or less similar to specific memory blocks. Importantly, all location sequence
23 differences were significantly smaller than the random baseline differences (all $ps<.001$).
24 Moreover, all blocks' location sequence differences were significantly smaller than the
25 5.93° v.a. distance between the nearest two circles (all $ps<.001$). Mean location sequence
26 differences of the last visual block (block 5) to the memory blocks 7-10 were also not

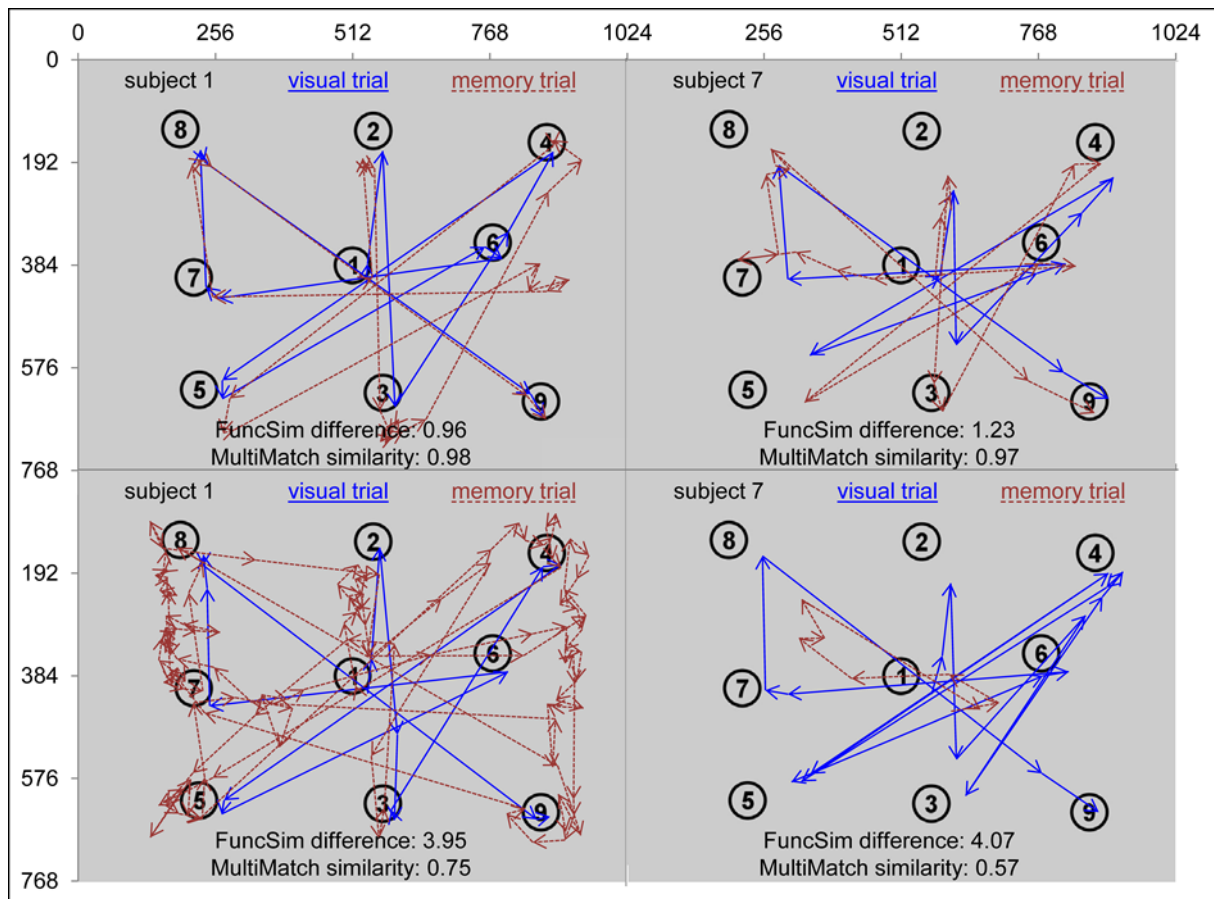
1 significantly different from the click-acceptance area of 3.06°v.a. around the targets. Thus,
 2 fixations landed approximately within the same circle area for each sub-action of the manual
 3 sequence whether visual targets were available or not. This sequential scanning of
 4 remembered target locations was robust across the memory blocks. Similarity scores,
 5 difference scores, and *t*-test values are summarized in Table 1. Exemplary scanpath pairs
 6 along with their FuncSim and MultiMatch comparison scores can be seen in Figure 4 and
 7 Figure S1. Corresponding slow motion eye and cursor movements (100 Hz) can be seen in the
 8 Supplementary Material.

9 Table 1. Mean location sequence MultiMatch similarity and FuncSim difference values of the
 10 comparisons of all trials of the last visual block (block 5) to all trials of the memory blocks
 11 (blocks 6-10) as well as to 10 scrambled derivatives per block 5 trial (5s). Values are
 12 presented along with the paired *t*-test values for the performed scanpath similarity
 13 comparisons (all against 5:5s, FuncSim values against the distance of 5.93°v.a. between the
 14 nearest two circles and against the click acceptance region of 3.06°v.a.). Significance levels
 15 are marked by asterisks (**p*<.05, ***p*<.01, ****p*<.001).

		5:6	5:7	5:8	5:9	5:10	5:5s
MultiMatch similarity	value [0-1]	.89	.92	.91	.90	.89	.74
	<i>t</i> to 5:5s	6.3***	9.1***	7.7***	4.1**	3.7**	
FuncSim difference	value [°v.a.]	3.76	3.50	3.45	3.47	3.34	10.88
	<i>t</i> to 5:5s	14.9***	15.0***	15.1***	19.4***	17.1***	
	<i>t</i> to 5.93°v.a.	7.8***	9.3***	9.6***	12.8***	11.5***	
	<i>t</i> to 3.06°v.a.	2.5*	1.7	1.4	2.2	1.3	



1
 2 Figure 3. Mean location sequence MultiMatch similarities (a) and FuncSim differences (b) of
 3 all trials of the last visual block (block 5) to all trials of the memory blocks (blocks 6-10) as
 4 well as to 10 scrambled derivatives per block 5 trial (5s). The MultiMatch y-axis measures
 5 similarity in normalized values and ranges from the minimum possible similarity of 0 to the
 6 maximum possible similarity of 1. The FuncSim y-axis measures difference in °v.a. and
 7 ranges from the screen diagonal of approximately 35°v.a. to the maximum possible similarity
 8 of 0°v.a. Error bars represent standard errors of the mean.
 9



1
 2 Figure 4. Example scanpaths of subject 1 (left) and subject 7 (right) during the visual (blue
 3 solid arrows) and the memory phase (red dashed arrows). The arrows represent the fixation
 4 sequence of individual trials. The number display was only visible during the visual phase.
 5 The upper two scanpath pairs represent one of the subjects’ most similar comparisons, while
 6 the bottom two scanpath pairs represent one of the subjects’ least similar comparisons. In the
 7 bottom left example, the memory-based scanpath contained more fixations than the visual
 8 scanpath. In the bottom right example, the memory-based scanpath contained fewer fixations
 9 than the visual scanpath. In FuncSim, both situations do not necessarily lead to decreased
 10 similarity, only if the averaged fixation locations per sub-action are dissimilar from the
 11 comparison partner. The FuncSim and MultiMatch scores for the comparison of each of the
 12 four scanpath pairs are indicated beneath each scanpath plot.

13

14 4 Discussion

15 When repeating a sensorimotor sequence for a sufficient amount of trials, participants
 16 acquire procedural memory for controlling the manual sequence, covert attention, and gaze, as
 17 indicated by target fixations (cf. Epelboim et al., 1995; Foerster & Schneider, 2015). These
 18 guiding fixations can be used to extract visual information about the target for effector
 19 movement calculation (e.g., Prablanc, Echallier, Komilis, & Jeannerod, 1979). However, the
 20 phenomenon of looking-at-nothing shows that empty target locations are also scanned from

1 memory (Brandt & Stark, 1997; Ferreira et al., 2008; Johansson et al., 2011, 2005, 2006;
2 Johansson & Johansson, 2013; Laeng & Teodorescu, 2002; Mast & Kosslyn, 2002; Noton &
3 Stark, 1971a, 1971b; Richardson & Spivey, 2000; Spivey & Geng, 2001). While this behavior
4 was robustly observed in explicit memory tasks, results were mixed concerning procedural
5 memory-based tasks, namely sensorimotor sequences (Flanagan et al., 2008; Foerster et al.,
6 2012). More specifically, single-session investigations could not find looking-at-nothing for
7 sensorimotor control (Flanagan et al., 2008), while a sensorimotor task that has been practiced
8 for days was accompanied by target location fixations in complete darkness (Foerster et al.,
9 2012). The present study aimed to reveal whether looking at remembered sensorimotor target
10 locations can be observed in a single session observation and thus independently from sleep
11 consolidation. Moreover, it was investigated how robustly remembered action targets are
12 scanned by the eyes when visual information is repeatedly not available provided that task
13 feedback is preserved.

14 To answer these two questions, eye movements were recorded while participants
15 performed a manual action sequence, i.e., a computerized version of the number connection
16 test or trail making test A (Army Individual Test Battery, 1944; Foerster & Schneider, 2015;
17 Reitan, 1958). In this sequential manual action task, participants had to click as fast as
18 possible on numbered circles in ascending order. The same configuration of numbered circles
19 had to be worked on in the same sequence for 50 trials to allow learning and accumulation of
20 LTM. To investigate looking-at-nothing during motor control, participants thereafter had to
21 click the sequence without visual targets on a blank screen from memory. This memory-based
22 action phase lasted for 50 trials, so that the robustness of fixating remembered action-target
23 locations without the availability of visual information could be studied.

24

1 ***4.1 Looking-at-nothing during single-session sensorimotor learning***

2 When visual information about targets was suddenly not available in the present
3 single-session study, performance suffered in line with the previous research (cf. Flanagan et
4 al., 2008; Foerster et al., 2012). Trial completion time increased due to more fixations.
5 Fixations and clicks were executed less accurately than with visual information available,
6 indicated by larger distances to the targets’ center. Probably, target locations stored in LTM
7 come with a certain imprecision. In the visual as well as the memory-based phase, most
8 fixations were concerned with the current target, indicated by eye-hand unit spans of about 0.
9 However, also subsequent targets were fixated during the visual phase (positive span), while
10 more fixations were directed towards completed targets during the memory-based phase
11 (negative span). Nevertheless, even when acting on remembered targets, eye movements
12 preceded cursor movements on the way to the current target location, indicated by positive
13 eye-hand target distance spans. Importantly, scanpaths were highly similar with and without
14 visual information when comparing trials of the last acquisition block to trials of the first
15 memory block. This result indicates that participants used the LTM information acquired
16 during the visual-targets phase to shift attention and gaze sequentially to the empty target
17 locations in the memory-based action phase. Taken together, when the motor target locations
18 were no longer visually marked, participants scanned the empty target locations on the screen
19 – a behavior known as looking-at-nothing (Ferreira et al., 2008; Johansson et al., 2011; Laeng
20 & Teodorescu, 2002; Mast & Kosslyn, 2002; Richardson et al., 2009; Richardson & Spivey,
21 2000), but less precise and less anticipatory than with visual targets available.

22 The observed gaze patterns are in line with Foerster et al.'s (2012) cup-stacking study.
23 In this study, systematic scanpaths were found in the absence of visual information in
24 complete darkness. Participants saccaded to manual target locations before the hand actually
25 reached them in complete darkness, i.e., fixations were executed to invisible targets. In
26 Flanagan et al. (2008), eye movements were only loosely coupled to action-target locations

1 when pointing to remembered targets or manipulating a bar behind a shutter. While
2 participants were trained for 14 days in cup-stacking before having to act in darkness
3 (Foerster et al., 2012), participants had only short acquisition phases within a single session in
4 the pointing and bar moving task (Flanagan et al., 2008). Therefore, the sensorimotor
5 procedures differed in the amount of practice and thus the level of automatization as well as in
6 whether sleep consolidation was possible. The present results indicate that looking-at-nothing
7 can be demonstrated within a single sensorimotor session. A sufficient amount of practice
8 rather than sleep consolidation seems to be required to elicit looking at empty target locations.
9 Looking-at-nothing for sensorimotor control seems to depend on sufficient LTM information
10 for controlling the sequence of attention shifts, eye movements, and manual actions.

11

12 ***4.2 Progress of looking-at-nothing when visual information is repeatedly unavailable***

13 Looking-at-nothing during sensorimotor tasks is applied, when visual action targets
14 are suddenly unavailable after a sufficient amount of practice with visual targets (here and in
15 Foerster et al., 2012). However, no study so far investigated gaze behavior when participants
16 have to perform a motor sequence repeatedly completely from memory, i.e., without the help
17 of visual action targets. Participants might learn that eye movements can no longer be used to
18 extract visual target information and thus abandon them. Alternatively, participants might
19 switch from an anticipatory oculomotor target scanning to a more reflexive action completion
20 monitoring. Finally, they may proceed or even intensify anticipatory target location scanning
21 after being familiarized with the lack of visual information. Such an anticipatory target
22 location scanning in the absence of visual target information could have advantages in its own
23 as will be described in the next section.

24 Here, performance and gaze measures were studied over the course of 50 trials without
25 visual targets on the screen. Most manual actions and eye movement measures changed back
26 in direction to the values when visual targets had still been available. Manual action

1 performance became less erroneous and faster – probably due to the reduction in fixations.
2 Fixations and clicks landed nearer to the current target’s center, indicating that sequential
3 scanning became more precise again. As auditory feedback about clicking success was still
4 provided during the memory-based action phase, participants could use it to further refine
5 their LTM representation of the target locations. Indeed, the consistent slightly negative value
6 of the eye-hand unit span indicates that participants more often re-fixated a completed target
7 location. In this way, they could check where exactly they had clicked correctly after hearing
8 the correct tone in order to refine their spatial LTM representation. However, participants did
9 not switch completely from an anticipatory to a reflexive gaze behavior, as indicated by the
10 positive eye-hand time spans in later memory blocks and positive eye-hand target distance
11 spans throughout the experiment. It seems that in addition to monitoring the success of their
12 actions, participants also resumed to use their eyes for guiding the cursor to the current target
13 location. Note that the performance and gaze measures in later memory-blocks might even
14 provide a more realistic picture of how participants use their attention and gaze to solve a
15 sensorimotor task without visual target information as the switch to the empty display is likely
16 accompanied by a surprise effect in the early memory-based trials (cf. Foerster, 2016;
17 Horstmann, 2015).

18

19 *4.3 Possible functions of fixating remembered action-target locations*

20 Why are visually available as well as remembered action-target locations sequentially
21 scanned during sensorimotor control? When visual information is present, important features
22 of an action target such as its orientation, surface, and size can be extracted by a fixation.
23 These features are important to calculate the needed hand-movement parameters such as
24 direction, force, and grip aperture (e.g., Prablanc et al., 1979; Prablanc, Pellison, & Goodale,
25 1986). However, even if visual targets are not available, saccading to a target location might
26 be functional (e.g., Ballard, Hayhoe, Pook, & Rao, 1997; Flanagan et al., 2008) as will be

1 outlined in the following. Alternatively, looking at remembered target locations in well-
2 learned manual action sequences could just be a by-product of learning and automatization.

3 Fixating an empty target location might facilitate declarative as well as procedural
4 memory retrieval. Recalling target features such as size or orientation from declarative
5 memory can help to adapt the effector movements to a specific target. There is evidence that
6 eye movements are indeed helpful for remembering previously presented material. When
7 recalling disappeared visual information, fixating the corresponding location helps
8 remembering the item and rebuilding a mental image (Cabeza, Ciaramelli, Olson, &
9 Moscovitch, 2008; Hebb, 1968; Johansson et al., 2011; Johansson & Johansson, 2013; Laeng
10 & Teodorescu, 2002; Mast & Kosslyn, 2002; Noton & Stark, 1971b; Olsen & Chiew, 2014).
11 Shifting attention and eye movements in a similar way as during encoding seems to help
12 extracting even more and higher quality information from a memory-stored picture
13 (Johansson, Holsanova, Johansson, Dewhurst, & Holmqvist, 2012). Memory performance for
14 a specific item is better when fixating the location where the item has been presented than
15 when forced to fixate a mismatching location (Johansson & Johansson, 2013). Eye
16 movements are even related to memory encoding and retrieval of material encoded from
17 verbal description only (Johansson et al., 2011, 2005, 2006), arguing that eye movements are
18 used to connect an internal representation and a location in the external world (see also
19 Richardson et al., 2009; Spivey & Geng, 2001 for a similar argumentation). Especially the
20 spatial relationship between memory items seems to be recalled easier when fixating the
21 remembered locations (Olsen & Chiew, 2014).

22 Importantly, also procedural memory of required actions might be facilitated by
23 looking at locations where these actions had been completed during prior executions.
24 Saccading to a potential target location might work similarly as perceiving an object with a
25 motor affordance – it activates an associated action from procedural memory (e.g.,
26 Mecklinger, Gruenewald, Weiskopf, & Doeller, 2004; Richardson, Spivey, & Cheung, 2001).

1 A procedural retrieval benefit could explain why looking-at-nothing is stronger with highly-
2 practiced sensorimotor tasks (here and in Foerster et al., 2012) than with unfamiliar
3 sensorimotor tasks (Flanagan et al., 2008). Taken together, shifting the eyes to remembered
4 manual action target locations might help to recall target features and learned actions.

5 Not only memory retrieval, but also memory encoding and consolidation might be
6 facilitated by looking-at-nothing. There is extensive evidence that rehearsal of spatial
7 information is disturbed when eye movements have to be shifted away from the to-be-
8 memorized locations (Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Johansson &
9 Johansson, 2013; Lawrence, Myerson, & Abrams, 2004; Lawrence, Myerson, Oonk, &
10 Abrams, 2001; Tas, Luck, & Hollingworth, 2016). This finding has been interpreted as
11 evidence for an eye-movement based rehearsal strategy as proposed by Baddeley (1986).
12 Looking-at-nothing as rehearsal strategy could explain why in the present study a higher
13 amount of fixations was concerned with completed target locations during the memory phase
14 than during the visual phase, indicated by a slightly negative eye-hand unit span. Presumably,
15 participants looked back at the correctly clicked locations in order to memorize the exact
16 position for the next trial.

17 Moreover, it has been argued that fixating remembered action-target locations has
18 direct benefits for hand-movement parameter calculation. Flanagan et al. (2008) argued that
19 saccading to hand-movement target locations might facilitate the computation of the hand-
20 movement command because these sensorimotor transformations are well-learned. Similarly,
21 Ballard and colleagues (Ballard et al., 1992, 1997) argue that the eyes might be used as an
22 deictic pointer for the hand movements in a “do-it-where-I’m-looking” manner. The idea is
23 that the current gaze position on a remembered target location is used as a deictic pointer for
24 the effector movement. Neurons that are tuned to zero-disparity at the fovea code the current
25 fixation location in external space (Ballard et al., 1997). Target locations remembered

1 respective to fixation points can then be retrieved in an externally-coded coordinate and can
2 be used to program the corresponding effector movement.

3 Finally, looking at remembered target locations, while performing manual action
4 sequences without visual information available, could just be an epiphenomenon of learning
5 and automatization. A task-adapted scanpath is learned and automatized during acquisition.
6 The automatized gaze routine might be applied during the memory-based manual routine even
7 if it is no longer beneficial to scan the target locations sequentially as no visual information
8 can be extracted (for an overview how motor routines are applied, see Ballard, 2015).
9 Scanning target locations sequentially is no prerequisite for LTM-based clicking, although
10 participants mostly did so spontaneously and robustly. Whether and how looking-at-nothing is
11 functional for motor control has to be investigated in future studies.

12

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17

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16

17 8 Supplementary material

18 Supplementary material can be found on the website of Vision Research. The file named
19 ‘FigureS1’ depicts example scanpaths based on the 1,000 Hz raw data samples of subject 1
20 (left) and subject 7 (right) during the visual (blue) and the memory phase (red). The number
21 display was only visible during the visual phase. The upper two scanpath pairs represent one
22 of the subjects’ most similar comparisons, while the bottom two scanpath pairs represent one
23 of the subjects’ least similar comparisons. The corresponding fixation sequences and their
24 FuncSim and MultiMatch comparison scores can be seen in Figure 4. The files with the prefix
25 ‘slowmo’ contain slow-motion eye (moving diamond and broken trace) and cursor (moving
26 dot and solid trace) movements (100 Hz) of the trial pairs presented in Figure 4 and FigureS1

1 (visual trials in blue and memory trials in red). The number display was only visible during
2 the visual phase. The correspondence to Figure 4 and FigureS1 is indicated by the file name
3 (subject[No] and low vs. high for type of similarity). In the files with the suffix ‘aligned’, the
4 movements were aligned per click action to facilitate the comparison of the eye-cursor
5 dynamics in the visual and the memory phase when acting on the same target.