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Brief Communication

Chunking movements into sequence: The visual pre-selection of subsequent goals

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ABSTRACT

The chunking of individual movements into sequences has been studied extensively from a motor point of view. Here we approach the planning of sequential behavior from a perceptual perspective investigating the sensorimotor transformations that accompany visually guided sequential behavior. We show that visual attention pre-selects subsequent goals only if two movements are planned to be carried out in rapid succession and therefore are integrated into one common action. This causes visual attention to select both intended goal locations in advance. In contrast, in more slowly executed motor sequences, the single movements are programmed one-by-one and subsequent movement goals are only later visually prepared ('just in time'). The visual selection of a subsequent goal location crucially depends on the speed of the planned sequence: the longer the inter-reach delay, the less visual attention is deployed to the subsequent goal initially.

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Chaining movements into sequence is a critical integral strategy 23 for forming complex behavior and accomplishing difficult goals. 24 Humans' intelligence is based in great part on the ability to form 25 complex action sequences. Examples of combinations of movement 26 primitives are ubiquitous, and range from locomotion to object-27 manipulation (Mennie, Havhoe, & Sullivan, 2007; Pelz, Havhoe, & 28 Loeber, 2001), eye movement control in reading (Vergilino-Perez 29 & Findlay, 2006), and language (Klapp, 2003; Lashley, 1951). In 30 order to optimize motion dynamics, it is often important not to 31 interrupt series of movements, e.g., when throwing a ball. Such flu-32 ent behavior is possible because many motor commands can be 33 pre-programmed, and the entire sequence can thus be carried out 34 without interruptions (Keele, 1968). Learning new behavior, then, 35 often means learning new sequences of well-known components 36 (Keele & Jennings, 1992; Sakai, Hikosaka, & Nakamura, 2004; Sakai, 37 Kitaguchi, & Hikosaka, 2003). Sakai and colleagues show that when learning a new sequential task, the initial performance is usually discontinuous, and becomes more efficient after several repeti-40 41 tions when the individual movement components are integrated in a unified structure (Sakai, Hikosaka, & Nakamura, 2004). 42

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In terms of neural activation sequencing individual movements involves more than just serial commands for executing movements in the required order. In fact, sequencing also requires the adjustment of spatiotemporal parameters of the individual components: the movements have to be chunked (Graybiel, 1998; Miller, 1956), i.e. combined into one common action plan, implying considerable crosstalk between the single movement units (Henry & Rogers, 1960; Smiley-Oyen, 1996). Pre-programming is advisable for the fluent chaining of movement components that do not need much online control, and that do not present a high load for working memory. Only if a motor sequence is too complicated, or in case of disturbances, single movement units have to be (re-)programmed online (Rosenbaum, Hindorff, & Munro, 1987; Smiley-Oyen, 1996). Indeed, examples show a gradual transition from preprogramming strategies to online control when the task gets increasingly complicated (Van Mier, Hulstijn, & Petersen, 1993).

For visually guided behavior, the pre-programming starts out as weighting and filtering of relevant visual information by means of selective attention. Actually, visual attention obligatorily selects the target of an upcoming goal-directed movement (Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995). If the priority lies in the fluent execution of a whole movement sequence, visually pre-selecting several subsequent goals can be advantageous, perhaps even necessary, in order to overcome sensorimotor delays (Day & Lyon, 2000). Indeed, previous work has

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shown that the visual system pre-selects multiple movement goals in advance of rapid motor sequences (Baldauf & Deubel, 2009, 2010; Godijn & Theeuwes, 2003; McPeek & Keller, 2001; McPeek, Keller, & Nakayama, 1999). This adds a perceptual perspective to the chunking and pre-programming of movement components

In case of slower sequences, however - e.g., when a single movement is executed, followed by a separate move several seconds later - both movements do not need to be chunked, and neither does the second movement goal need to be visually prepared instantaneously. According to Ballard, Hayhoe, and Pelz (1995), actors prepare for such slower task sequences with a 'just-in-time strategy': target objects are selected not until they become relevant (Hayhoe & Ballard, 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003). Hence, the timing of movements seems to be key to how far ahead visual information is preselected.

Here, we explore the timing constraints under which movements get chunked and subsequent goals are visually pre-selected within the same sensory-motor loop. We propose that the visual pre-selection of subsequent goals reflects whether or not two movements are chunked together.

1. Experiment 1: rhythmic double-reach sequences

For the primary task, we instructed participants to perform double-reaches to two of several peripheral placeholders. The critical manipulation was that both reaches had to be executed in a certain rhythm. During the preparation period, i.e. the short time 95 interval after the go-signal but before the onset of the movement, we probed the distribution of visual attention with a secondary letter-discrimination task.

Participants adjusted both the latency and duration of the second movement such that the inter-reach interval (IRD) increased gradually over the four timing conditions (Fig. 2). The latency of



Fig. 1. Temporal sequence of events. (A) Experiment 1: at the beginning of each trial two acoustic beeps instructed the rhythm of the subsequent movement sequence (100 ms, 300 ms, 500 ms, or 700 ms inter-tone-interval). After a random interval a central arrow indicated one of the surrounding mask elements as the first goal. The participant responded to the onset of this movement cue by reaching the indicated position, then moving on to the next-but-one position in a clockwise direction. The inter-reach delay (IRD) should be the same as the instructed inter-tone interval. (B) Experiment 2: all mask elements (including both goal locations) were deleted before movement onset. Consequently, double-reaches had to be performed from memory.

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1.1. Methods

Nine students participated in Experiment 1. The participant sat in front of a pointing plane onto which the visual stimuli were projected (see Supplementary material). Hand and eye position were continuously recorded.

Throughout each trial the subject had to fixate the central cross, the starting point of the reach movements (Fig. 1A). After a random interval, two acoustic beeps were presented with an inter-beep interval of 100, 300, 500, or 700 ms. The subject had to memorize the inter-beep interval and then execute a double reach sequence in the same rhythm as soon as a movement cue appeared at the fixation cross. The first movement had to be directed to the cued placeholder and a subsequent movement led to the second-next placeholder in clockwise direction. Participants were instructed to perform the movements as accurately as possible and in the instructed rhvthm.

To probe the distribution of attention in the visual field during the movement preparation, we used a secondary letter discrimination task: 50 ms after the onset of the movement cue all placeholder elements were briefly switched to letter symbols. One randomly chosen element changed into a critical discrimination target (DT), resembling a digital 'E' or '3'. The other placeholders changed into task-irrelevant distractors (digital 2's and 5's). After a presentation time of 150 ms - well before the first movement started - the discrimination target and distractors were post-masked. At the end of each trial the participant had to respond whether an 'E' or '3' had been presented at any location during movement preparation.

Since the combination of spatially accurate double-pointing sequences and precise timing of the movement speed is a rather complicated task, the various timing conditions were blocked such that within one block of 32 trials the instructed sequence timing stayed the same; the order of blocks was randomized. All other conditions were intermixed trial-wise. The percentage of correct responses in the secondary discrimination task provides a measure of how visual resources were distributed in the visual field.

1.2. Results

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Instructed Delay: 100ms Frequency [%] Instructed Delay: 300ms 10 5 0 5 Instructed Delay: 500ms Frequency [%] Instructed Delay: 700ms Frequency [%] n n Latency of 1st / 2nd move Duration of 1st / 2nd move Inter-Reach Delay (IRD)

Fig. 2. Timing of double-reaches in the four different timing conditions of Experiment 1: histograms on the left show the latency distributions of the first (filled) and second (open bars) movements. Panels in the central column show the durations of both reaches; distributions of the actual inter-reach delays on the right.

the first movement component did not vary systematically (seeSupplementary material).

Fig. 3A shows the discrimination performances at the first and second movement goal (and other, task-irrelevant locations) as a function of the sequence timing. A two-way ANOVA with the first factor 'Position of the Discrimination Target' (levels: 'DT at the 1st goal', 'DT at the 2nd goal' and 'DT at a movement-irrelevant location') and the second factor 'Instructed Inter-reach delay' (IRD, levels: 100, 300, 500, and 700 ms) revealed a significant main effect of the relative 'Position of the Discrimination Target' (F[2,16] = 15.0,p < .001) and an interaction of both factors, F(6,48) = 2.87, p < .02. Irrespective of the timing condition participants were successful in discriminating the target letters when presented at the 1st goal location, F(3,24) = .84, p > .48. In contrast, performance was close to chance when the discrimination target appeared at one of the movement-irrelevant positions. In both these cases, the various timing conditions did not have any systematic or statistically significant effect on the discrimination performance, F(3,24) = 1.26, p>.31.

Interestingly, only the discrimination performance at the 2nd goal varied systematically across the four timing conditions (F[3,24]=3.80, p < .02), suggesting that this position was only selected at timing conditions for which sequence production was planned to be rapid. At an IRD of 100 ms, discrimina-tion performance at the 2nd goal was at 75% correct decisions, and significantly different from the baseline performance at the movement-irrelevant locations, t(8) = 2.51, p < .03.



Fig. 3. Perceptual performance in the secondary letter discrimination tasks. (A) Experiment 1: double-reach sequences with all goals visible during movement execution. The discrimination performance for the 1st goal (blue) was constant at about 83% across the four timing conditions. Discrimination performance for the 2nd goal (red) decreased with longer inter-reach-delays. When the sequence was executed slowly (i.e., with an inter-reach-delay of more than 400 ms) the 2nd goal is not preselected. Discrimination performance was close to chance level (50%) at irrelevant positions (black). Dashed lines represent the discrimination performance in a subset of data in which only correctly timed trials were included. (B) Experiment 2: if no visual landmarks were present during movement execution, discrimination performance at the 1st and 2nd reach goal was at a constant high level, independent of the inter-reach delay. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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To determine the IRD threshold at which the pre-selection of the 2nd goal significantly dropped, we calculated single contrasts between the discrimination performance in speeded trials (100 ms IRD) and the respective performances for all other timing conditions. In trials with 300 ms IRD, the 2nd goal was selected at a level similar to that in trials with 100 ms IRD, t(8) = 1.01, p > .34. However, already in trials with 500 ms IRD, the performance at the 2nd goal started to drop, and was significantly different from the corresponding performance in the 100 ms IRD condition, t(8) = 3.35, *p* < .01.

In a further step, we analyzed whether the (pre-)selection of the reach goals depends more on how fast the participants intended to perform (i.e. the instructed timing), or - alternatively - on how fast they actually performed the sequence. To disentangle these two possibilities in our analysis, we discarded all trials where the actual sequence timing did not correspond to the instructed timing. As can be seen from the distribution of IRDs (Fig. 2), this slight mismatch occurred occasionally. This was in part due to general biases in the reproduction of the instructed time intervals, but also due to intertrial variations. When we included only trials in which the actual IRD was within a range of the instructed IRD \pm 100 ms (Fig. 2, vertical red lines) this rigorous discarding criterion lead to an even more pronounced linear trend in the visual selection of the 2nd goal (Fig. 3, dashed): discrimination performance was even better before rapid sequences if trials with accidentally too long IRD 184 **Q1** were discarded. (For interpretation of the references to color in this sentence, the reader is referred to the web version of the article.) The opposite was true for very slow sequences. Here, the discarding of trials with too short IRD further decreased the perceptual performance at the second goal.

2. Experiment 2: reach sequences without visual landmarks 190

The results of Experiment 1 suggest that a subsequent movement goal is visually prepared in advance of sequence initialization if - and only if - the two movements follow each other closely. On the contrary, there is apparently no need to pre-select any subsequent goal location if the time between two reach components is long enough to prepare the reaches one-by-one and 'just in time' (Ballard et al., 1995).

In Experiment 2, we directly tested this interpretation by restricting the time when visual information about the 2nd goal was available. We hypothesize that participants would have to preselect the subsequent goal independently of the intended sequence timing when visual information about the goal positions was no longer available for the remainder of the trial. Under these conditions, the 'just-in-time' selection strategy would no longer be successful, and the actors would be obligated instead to pre-select all positions at once, and store this information over the inter-reach delay.

Experiment 2 employed the same task structure, but all visual landmarks in the periphery were extinguished right after postmasking the discrimination targets for 100 ms (Fig. 1B). For the rest of the trial, the central eye fixation remained the only visual stimulus in the field and the sequence thus had to be executed from memory. Importantly, no visual information about the 2nd reach goal was available after completion of the 1st reach.

The movement performance in Experiment 2 was similar to Experiment 1 (see Supplementary material). Neither the average latency, nor the movement duration differed significantly between both experiments.

In contrast to Experiment 1, the discrimination performance at the 2nd goal did not vary across different speeded motor sequences. A one-way ANOVA over this subset of data showed no significant effect of the 'instructed Inter-reach Delay' on the selection of the second movement goal, F(3,18) = .35, p > .79. Rather, the attentional selection of the 2nd goal remained stable, at a level of about 78%.

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3. General discussion

We hypothesized that the degree to which the subsequent goals are visually pre-selected in advance of sequence initialization depends on the planned pace of the sequence. Specifically, we anticipated that subsequent goals are only pre-selected in parallel if a *rapid* reach sequences is planned.

Results from Experiment 1 confirm this hypothesis. Before rapid sequences, both goals were visually pre-selected. However, when actors were instructed to pause at the first movement goal for more than 400 ms before continuing with the second reach, attentional selection was restricted to the first goal position, and the 2nd goal was not selected more than other, reach-irrelevant locations. The extent to which a subsequent reach goal was pre-selected was a (almost linear) function of the inter-reach delay between both movement components; the shorter the inter-reach delay, the better was the 2nd goal pre-selected.

The IRD specifically affected the pre-selection of the 2nd goal, ruling out a generally increased arousal state. Interestingly, the good perceptual performance at the 1st goal was not diminished if the second position was co-activated. This is in line with previous findings, which compared motor sequences of different lengths (Baldauf & Deubel, 2008; Baldauf, Wolf, & Deubel, 2006), and suggests that the sum of visual resources that are distributed in the visual field depends on the current needs of the (motor) task.

Although participants adjusted the IRD according to the instructions, the actual timing of the reach sequences was not perfect in two respects: first, we observed a tendency towards the centre of the four timing conditions, resulting in an overproduction of very short intervals and an underproduction of long IRDs. Second, the IRDs confirm Weber's law that timing is noisier for longer time intervals. The fact that the actual timing differed systematically from the instructed timing allowed us to show that the pre-selection of subsequent goals depends more on the actual rather than the *intended* movement pace, exaggerating the (linear) decrease in discrimination performance. This result further emphasizes the strong influence of action preparation on the distribution of sensory resources.

Experiment 1 revealed a transition from pre-programming to a 'just-in-time' strategy with increasing IRD. Subsequent motor goals may be only pre-selected if a serial preparation is impossible or uneconomical. In Experiment 2 we made it impossible to select the 2nd goal "just in time" by extinguishing the spatial locations that mark the goal positions before sequence initialization. We therefore forced the actors to pre-select all movement-relevant positions in advance - irrespective of sequence timing. The stable pre-selection of to-be-remembered goals shows that also task constraints and strategies can affect the grouping of movements. This result matches data on the neural representation of subsequent motor goals in cells of the posterior parietal cortex (Baldauf, Cui, & Andersen, 2008). When monkeys performed memory-guided double-reach sequences without visual landmarks present the representation of the 2nd goal was even more stable if the motor sequences were interrupted by long inter-reach delays (>650 ms). In order to keep the representation active over the prolonged memory period, the 2nd goal had to be represented even better from the beginning.

We conclude that movements are chunked and subsequent goals are visually pre-selected if a stepwise preparation of the individual movements is impossible, e.g. because the visual information is no longer available, or because the time between the movements is not long enough. The distribution of visual atten-

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tion is thus an indicator of the extent to which two movements 286 are combined into one common action plan. Specifically the visual 287 pre-selection of subsequent movement goals mirrors the transi-288 tion from a stepwise movement preparation to chunked movement 280 sequences. Inter-reach delays in the range of 400 ms are thereby 200 most critical: if two reach movements are planned to succeed each 201 other within less than a 400 ms they are chunked and all goal 202 locations are visually prepared in advance. It remains to be seen 203 whether the 400 ms interval can be generalized to motor sequences 294 in other effector systems. 295

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Appendix A. Supplementary data 301

Supplementary data associated with this article can be found, in 302 the online version, at doi:10.1016/j.neuropsychologia.2011.01.041. 303

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