1 Overlap of movement planning and movement execution reduces reaction time.

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10 RUNNING TITLE: Overlap of movement planning and execution

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25   Abstract

26   Motor planning is the process of preparing the appropriate motor commands in order to

27   achieve a goal. This process has largely been thought to occur before movement onset and

28   traditionally has been associated with reaction time. However, in a virtual line bisection task, we

29   observed an overlap between movement planning and execution.

30   In this task performed with a robotic manipulandum, we observed that participants (N=30)

31   made straight movements when the line was in front of them (near target), but often made

32   curved movements when the same target was moved sideways (far target, which had the same

33   orientation) in such a way that they crossed the line perpendicular to its orientation.

34   Unexpectedly, movements to the far targets had shorter reaction times than movements to the

35   near targets (mean difference: 32ms, SE: 5ms, max: 104ms). In addition, the curvature of the

36   movement modulated reaction time. A larger increase in movement curvature from the near to

37   the far target was associated with a larger reduction in reaction time. These highly curved

38   movements started with a transport phase during which accuracy demands were not taken into

39   account.

40   We conclude that an accuracy demand imposes a reaction time penalty if processed before

41   movement onset. This penalty is reduced if the start of the movement consists of a transport

42   phase and if the movement plan can be refined with respect to accuracy demands later in the

43   movement, hence demonstrating an overlap between movement planning and execution.

44   New and Noteworthy

45   In the planning of a movement, the brain has the opportunity to delay the incorporation of

46   accuracy requirements of the motor plan in order to reduce the reaction time by up to 100ms

47   (average: 32ms). Such shortening of reaction time is observed here when the first phase of the

48   movement consists of a transport phase. This forces us to reconsider the hypothesis that motor

49   plans are fully defined before movement onset.

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Introduction

Motor planning is the process of selecting a goal and the appropriate motor commands in order to achieve this goal. This process has largely been considered part of a single building block that specifies all the characteristics of the ensuing movement. For instance, the latest theories of motor planning suggest that the "complete specification of the motor command" occurs before movement start (Wong et al., 2015). Optimal control theory (Harris and Wolpert, 1998; Todorov and Jordan, 2002; Scott, 2004) also suggests that the control policy is defined before movement onset. In case of multiple possible motor plans, the average of these control policies is used early on and the appropriate motor plan is selected later (Stewart et al., 2014; Gallivan et al., 2016a, 2016b).

The idea that a movement should be completely pre-planned before its execution is reminiscent of the work of Henry and Rogers in the 60's (Henry and Rogers, 1960). In their memory drum theory of movement preparation, they suggested that planning took longer for more complex movements, which was reflected in the movement reaction time (RT). More precisely, Henry and Rogers (1960) found that reaction time was shorter when simply lifting a finger than when reaching to a goal with a single movement or with a more complicated sequence of movements. However, in these experiments, distance to the target or accuracy demands (i.e. how accurate the movements must be, which depends on target size, etc.) are confounded with movement complexity. These factors nonetheless influence movement reaction time. For instance, Laszlo and Livesey (1977) found that reaction times were 100ms shorter for non-goal directed movements (when accuracy requirements were removed) than for goal directed movements with strict accuracy demands (while movement complexity was matched). In contrast, loosening accuracy requirements by increasing the width of the target does not influence reaction time (Quinn et al., 1980; Orban de Xivry, 2013; Orban de Xivry and Lefèvre, 2016). Considering that non-goal directed movements are movements with minimal accuracy requirements, there seems to be a conflict between the effect of loosening or completely removing accuracy demands on reaction time (i.e., only the latter influences reaction time). The aim of this paper is to resolve this apparent contradiction by looking at the actual influence of accuracy demands on movement reaction time.

81   To do so, we set up a line bisection task in which the position of the lines forced the participants

82   to adopt different strategies for different conditions, but accuracy demands were identical

83   across conditions. As a result, we observed that when the movement began with a transport

84   phase (requiring less accuracy), the reaction time was much shorter than when the participants

85   moved directly towards the center of the line. In other words, delaying the influence of accuracy

86   demands on movement kinematics (because of the transport phase) led to shorter reaction

87   times, which were up to 100ms shorter than in the control condition. That is, delaying the

88   planning for movement accuracy during execution led to a substantial decrease in reaction time.

89   These data suggest that increasing the overlap between movement planning and movement

90   execution leads to a reduction in reaction time.

91   Methods

92   Participants

93   Thirty one healthy young participants were recruited to participate in our experiment. All

94   participants had no known history of neurological disorders, no recent or residual consequences

95   of upper-limb trauma, were right-handed, between 20 and 38 years old (mean: 24 years) and

96   had normal or corrected-to-normal vision. All of them gave written informed consent. The

97   procedures were approved by the Université catholique de Louvain Ethics Committee and were

98   in accordance with the latest version of the Declaration of Helsinki.

99   Experimental setup

100   Participants sat in front of a robotic arm (Endpoint Kinarm, BKin Technologies, Kingston,

101   Ontario, Canada). They controlled the handle of the robot with their right hand in order to move

102   a white cursor (disk with diameter of 0.5cm) that was displayed on a horizontal mirror

103   positioned above the arm. The cursor and targets of interest were displayed on a screen placed

104   tangentially above the mirror and were reflected by it. Because the mirror was halfway between

105   the handle and the screen (52" monitor (16:9 ratio) with refresh rate at 75Hz), the cursor

106   appeared to be positioned at the same position in space as the hand after horizontal positions

107   were properly calibrated. With this setup, subjects could not see their hand and the displayed

108   cursor was the only available visual feedback of their arm position.

109 The robot controlled the display through custom-made MATLAB (R2007) programs uploaded to

110 a real-time computer. It also monitored hand position, velocity and acceleration at 1000Hz.

111 Kinematic and dynamic data were stored on a PC for offline analysis.

112 Protocol

113 In this experiment, participants were instructed to perform a line bisection task by moving the

114 cursor and crossing lines projected on the horizontal mirror at their middle point (Fig.1). At the

115 start of each trial, participants were required to bring the hand cursor inside a 2cm x 2cm

116 orange square that was located on the lower right part of the workspace. When the cursor was

117 inside the square, an orange line appeared at one of four possible positions. There were three

118 possible line lengths (10, 15 or 20cm). The participants were instructed to drive the cursor

119 through the middle of the line with a continuous and smooth movement. For each position, the

120 line was presented either horizontally or vertically (see Fig.1). The center of horizontal lines was

121 either 5cm or 22.5cm on the left of the starting point and 10cm above it. The center of the

122 vertical lines was 10cm on the left of the starting point and either 5cm or 22.5cm above it. With

123 this design, each line position was associated with only one line orientation. Lines were

124 presented after a random time interval once the hand cursor was inside the starting position

125 (1000-1500ms) so that the participants could not anticipate where and when the next line

126 would appear. Once the participants crossed the line, they were required to go back to the

127 starting position and the next trial was initiated after an inter-trial time interval of 200ms.

128 Participants were instructed to move at a comfortable speed. Each block consisted of 5 sub-

129 blocks of 12 trials (2 line orientations x 2 distances x 3 lengths) that were randomly presented.

130 Participants performed two blocks for a total of 120 trials.

131 Movement curvature was measured as the average distance between the actual hand trajectory

132 and a straight line linking movement onset and offset. Reaction time (RT) was defined as the

133 time between the line appearance and the start of the movement, which corresponded to the

134 time at which the vectorial velocity reached 2cm/s. Trials in which movement onset were

135 detected before target appearance or more than 750ms after target appearance were rejected

136 from the analysis (8% of the trials). Movement duration was computed as the time between

137 movement onset and when the hand cursor crossed the line (i.e., offset). The absolute position

138 error was computed as the distance between the hand cursor and the middle of the line at the

139 time of line bisection. Finally, to quantify movement variability of these 2D movements, we first

140 normalized the time of movement (0% is the movement onset and 100% is line bisection) and

141 resampled each movement in 0.4% time intervals (250 samples) using spline functions (as in

142 Orban de Xivry et al., 2011). For each of the 250 samples, we computed the minimum distance

143 between the 2D cursor position and the average movement trajectory. Across-movement

144 variability was equal to the average distance across movements. This measure of variability was

145 normalized by its value on the first sample (at movement onset) in order to account for inter-

146 subject variability.

147 Changes in line length and in line position ensure that the participants were not aware that they

148 had to reach the exact same point. However, the influence of the line length parameter on the

149 behavior was not analyzed. Data were therefore merged according to the remaining conditions.

150 For each participant, median reaction time (instead of mean given the skewness of reaction

151 time data) and mean curvature, absolute position error, movement duration and normalized

152 variability were computed. They were used as dependent variables in two repeated-measure

153 ANOVAs with 2 within-subject factors: *orientation of the line* (horizontal or vertical) and *distance*

154 *of the line* (near or far). Tukey's post-hoc tests were used for one-to-one comparisons. Changes

155 in the variables of interest were obtained by subtracting their value for the near target from the

156 same measure for the far target independently for each line orientation.

157 Statistical tests were performed with Statistica (Dell Inc.). Level of significance was 0.05. Effect

158 sizes were evaluated through partial eta-square. The effect of period (1st or 2nd half of the

159 experiment) was never found significant, neither as main effect nor in an interaction (absence of

160 learning effect). This effect is thus not reported in the Results section.

161 One participant was excluded from the analysis because he failed to comply with the task

162 instructions and did not aim at the center of the lines.

163 Results

164 We asked participants to bisect lines of different length with a cursor. In this task, the

165 directionality of the target led to a wide between-participant variety of hand paths. This variety

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166   of strategies is illustrated in Fig.1 for two participants. The first participant presented in Fig.1

167   (participant #19, panel A) exhibited simple and slightly curved movements towards the near

168   targets. The velocity profile of these movements to the near targets exhibited a single peak. In

169   contrast, the movements to the far targets were highly curved and the corresponding average

170   velocity profiles exhibited a local minimum (inset of Fig.1A, solid grey trace). In other words, this

171   participant chose a curved hand trajectory in such a way that it crossed the line perpendicular to

172   it. However, there was a lot of variability across participants in terms of movement curvature.

173   Some participants, as the one illustrated at Fig.1B, did not exhibit highly curved movements for

174   the far targets and the velocity profiles for both targets only exhibited a single peak (inset of

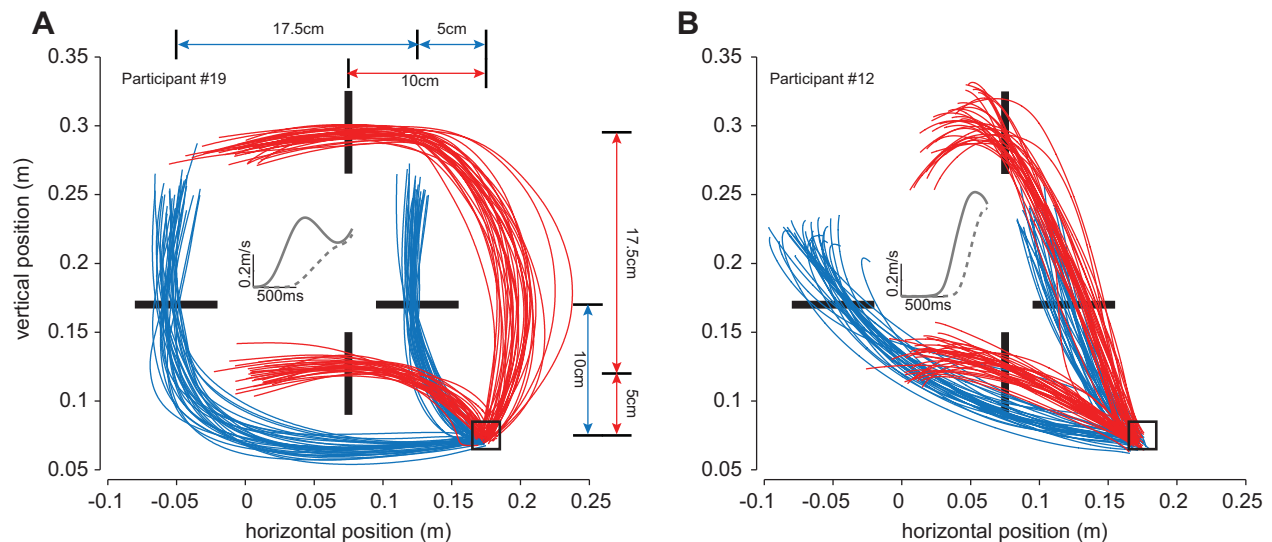175   Fig.1B, solid and dotted grey traces).

Figure 1

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Figure 1: During the line bissection task, participants adopted very different behaviors as illustrated by the hand
trajectories from two typical subjects. Participant #19 (panel A) exhibited curved movements for the far targets while
participant #12 reached straight to the center of the line for both near and fat targets. For each subject, the starting
position is represented by the square and the target lines are represented as black bars. For clarity, the lines are
shorter in the illustration than in reality (10, 15 or 20cm). Hand trajectories of all the trials for these participants are
given for horizontal lines (blue traces) and for vertical lines (red traces). The distance between the different targets
and the starting position are given in panel A. For each subject, the inset in the middle of the figure represents the
average vectorial velocity trace (aligned on time of reaching to the target) for horizontal near and far targets (resp.
dotted and solid lines). Body midline was aligned with 0 on the horizontal axis.

186   This feature of the movements was characterized by the movement curvature, which was much

187   higher for movements to the far than to the near targets (main effect of target distance:

188    $F(1,29)=150.69$, $p<0.001$, partial eta-square: 0.84, Figure 2A). In addition, the change in

189   movement curvature was slightly larger for vertical than horizontal lines (interaction between

190   orientation and distance: $F(1,29)=5.94$, $p=.02$, partial eta-square: 0.17). Nonetheless, the effect

191   of target distance on movement curvature was highly significant for both line orientations

192   (Tukey's post-hoc tests: $p<0.001$ for both).

193   Despite being more curved, movements to the far targets had shorter reaction times than

194   movements to the near targets (Figure 2B). This effect gave rise to a main effect of target

195   distance on reaction time ($F(1,29)=46.36$, $p<0.001$, partial eta-square: 0.61), but also to an

196   interaction between line direction and target distance ($F(1,29)=8.62$, $p=.006$, partial eta-square:

197   0.23), which was due to the fact that the decrease in reaction time with target distance was

198   more pronounced for horizontal lines than for vertical lines. However, this effect remained

199   significant for both line orientations (Post-hoc test: $p<0.001$ for both orientations; ΔRT

200   Horizontal targets (H): 40ms±5.8ms (mean±SE); ΔRT Vertical targets (V): 24ms±5.5ms). That is, it

201   took less time to start a more curved movement towards a farther target. Nonetheless,

202   accuracy to near and far targets was essentially identical (absolute position error: main effect of

203   target distance: $F(1,29)=0.55$, $p=0.46$, partial eta-square: 0.018). However, this change in

204   reaction time was insufficient to compensate for the longer movement duration (from

205   movement onset to movement offset) for the far target compared to the near target. Indeed,

206   the movements towards the far targets were, on average, 320ms (SE: 24ms) longer than the

207   movements towards the near target (main effect of target distance: $F(1,29)=183.22$, $p<0.001$,

208   partial eta-square: 0.86). Participants that reduced their reaction time by 80-100ms from near

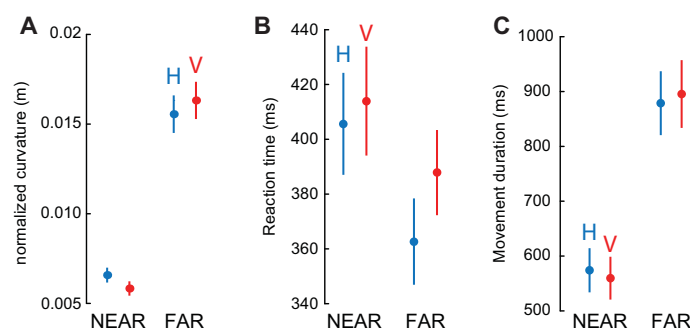209   to far targets had a corresponding increase in MT of 300-400ms.

Figure 2

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214   Similar to movement curvature, the pattern of within-subject variability across movements was

215   different for the near and far targets. While across-movement variability only slightly increased

216   for movements to the near target, there was a marked transient increase in across-movement

217   variability for movements to the far target. Movement variability peaked around the middle of

218   movement before decreasing to levels similar to those for the near target as the participants

219   approached the target (Fig.3). At the time of line bisection, variability was higher for the far

220   target than for the near target (main effect of target distance: $F_{(1,29)}=19.4$, $p<0.001$, partial eta-

221   square: 0.4). This effect was present for the horizontal lines but not for the vertical ones

222   (interaction between line orientation and target distance: $F_{(1,29)}=8.32$, $p=0.007$; post-hoc

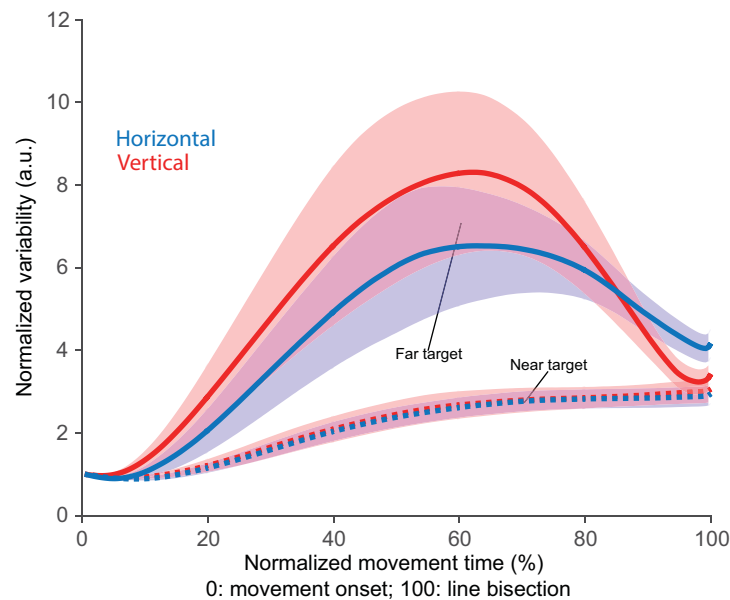223   Tukey test: H: $p<0.001$; V: $p= 0.3$).

228   There was a lot of variability in how the curvature of movements changed with target distance

229   (compare Fig.1A and 1B). Therefore, we tested whether participants who exhibited large

230   changes in movement curvature had a larger change in reaction time with target distance than

231   people who performed straight movements towards the target independent of target distance

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232   (Fig.1B). To do so, we correlated the change in median reaction time from near to far targets
233   with the change in movement curvature from near to far targets. This was performed
234   independently for each line orientation (Fig.4). We found that the changes in curvature with
235   movement distance were correlated with the change in reaction time with movement distance
236   across subjects (H: r=-0.45, p=0.01; V: r=-0.54, p=0.002). It should be noted that reaction time
237   and curvature for each distance and line orientation were not correlated, probably because of
238   the large inter-individual differences in average reaction time. Similarly, the change in reaction
239   time was uncorrelated with the change in absolute error at the end of the movement (H: r = -
240   0.23, p = 0.23; V: r = 0.03, p = 0.86) or the change in endpoint movement variability (H: r = -0.08,
241   p = 0.66; V: r = 0.2, p = 0.28).

242   The change in target distance not only influenced movement curvature, but also movement
243   speed (main effect of target distance on movement peak velocity: $F(1,29)=137.9$, $p<0.0001$;
244   Mean±SE: Near targets: 0.44±0.053 m/s; Far targets: 0.56±0.061 m/s). In addition, peak velocity
245   of the movement was correlated with reaction time. We observed that an increase in
246   movement speed was coupled with an increase in reaction time (H: r=0.54, p=0.02; V: r=0.35,
247   p=0.057). In order to make sure that the effect of movement curvature on RT was independent
248   of movement speed, we performed a partial correlation analysis and found that, even when the
249   change in movement speed was taken into account, changes in movement curvature and
250   changes in movement reaction time were still correlated (H: r=-0.38, p=0.038; V: r=-0.48,
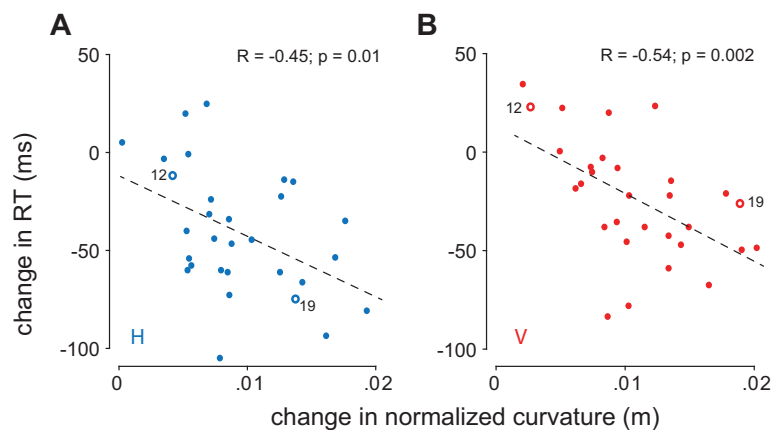251   p=0.007).

Figure 4

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253 **Figure 4:** Participants who exhibited a larger increase in movement curvature from far to near targets also exhibited
254 a larger decrease in reaction time with target distance. This was true for both line orientations. Left panel is for
255 movements towards horizontal lines and right panel for vertical lines. In each panel, the two points that are
256 highlighted (open circles) and numbered correspond to the values for the two subjects illustrated on Fig.1.

257 Discussion

258 In this study, we showed that the reaction time of a reaching movement was affected by the
259 chosen hand trajectory. Curved movements made toward a more distant target had, on
260 average, a shorter reaction time than straighter movements made toward a nearer target.
261 Furthermore, this effect depended on the curvature of the movement. A larger increase in
262 movement curvature for the far compared to the near target was accompanied by a larger
263 decrease in movement reaction time. This decrease in reaction time was not correlated with
264 movement accuracy or variability.

265 Confounding factors

266 Movement complexity, movement extent or the presence or absence of a sequence of sub-
267 movements differ between movements to near and far targets. Interestingly, all these possible
268 confounding factors would result in an increase in reaction time for movements towards the far
269 targets compared to the near targets (i.e., opposite to what was observed). For instance, several
270 studies have shown that an increase in movement complexity is accompanied by longer reaction
271 times (Henry and Rogers, 1960; Klapp et al., 1974; Christina and Rose, 1985). Similarly, larger
272 movements are traditionally associated with longer reaction times (Munro et al., 2007; Falco et
273 al., 2013). Finally, an increased number of movement phases, such as the ones we sometimes
274 observed towards the far target, has been associated with an increase in reaction time (Klapp,
275 1995).

276 Taking accuracy demands into account later

277 In contrast to Laszlo and Livesey (1977) who showed that the presence or absence of accuracy
278 demands had a substantial impact on reaction time, we observed a modulation of reaction time
279 with target distance despite matched accuracy demands across conditions. Based on our results,
280 we hypothesize that, while movements to the near targets had to take the accuracy demand
281 into account before movement onset, the influence of accuracy demands for movements to the
282 farther target could be delayed to later during the movement. As a result, reaction times were
283 shorter for the farther target.

284   This hypothesis is consistent with the fact that movement variability increased during the first

285   phase of the movements towards the far target (a sign that accuracy demands are not so

286   important early in the movement) but was reduced during the second phase of the movement

287   (Fig.3). This is also compatible with the existence of two movement phases: a transport phase

288   during which across-movement variability increased and a second phase during which

289   movement variability was reduced. In contrast, movement variability remained much smaller

290   during movements towards the near target (Fig.3), which suggests that the existence of these

291   two phases is specific to movements to the farther targets.

292   This hypothesis can also account for the correlation between movement curvature and reaction

293   time (Fig.4). Following this hypothesis, highly curved movements (e.g. Fig.1A), which often

294   consisted of two velocity peaks, are composed of two sub-movement parts: a first sub-

295   movement that aimed at transporting the hand to an intermediate location while the second

296   sub-movement was responsible for bringing the hand to bisect the target line as accurately as

297   possible. In contrast, participants who moved their hand directly towards the far target (e.g.

298   Fig.1B) did not exhibit such a transport phase and directly aimed at the center of the line.

299   Therefore, for these movements, accuracy demands were taken into account prior to

300   movement initiation. This suggests that participants who postponed the processing of accuracy

301   demands had a shorter reaction time for far targets compared to near targets whereas

302   participants who did postpone accuracy demands exhibited similar reaction times for both

303   target distances. Similar effects of accuracy demands on reaction time have been found for

304   catch-up saccades that are executed during visual tracking of moving targets (Orban de Xivry

305   and Lefèvre, 2007). Saccadic eye movements have been thought to be ballistic because of the

306   limited visual inputs during their execution. Yet, when saccades were made towards a moving

307   target, some of these movements exhibited clear changes in direction (i.e. curvature) during

308   their execution (Schreiber et al., 2006). Similar to the reaching movements in this study, curved

309   saccades had a shorter reaction time than straight saccades. That is, saccades that were

310   updated online to integrate new information had a shorter reaction time than the straighter

311   saccades that were not modified during the movements (Schreiber et al., 2006). Together with

312   our results, this suggests that the brain can either decide to start a movement early and to

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313   modify it later on the basis of new incoming information or that it can delay the onset of a

314   movement and make it more straight (i.e. no change in goal during movement execution).

315   Importantly, our data highlight that taking accuracy demands into account in the planning of

316   movement trajectory is not a black or white process as suggested by the study of Laszlo and

317   Livesey (1977). Rather, we observed a continuum of change in reaction times. For straight hand

318   trajectories to the far targets, accuracy demands are taken into account before movement

319   onset. For such straight movements towards the target, reaction time is not influenced by the

320   loosening of accuracy demands (as in Orban de Xivry, 2013; Orban de Xivry and Lefèvre, 2016)

321   but just by their presence. Alternatively, delaying the effect of accuracy demands on hand

322   trajectory (by refining movement plan during its execution) resulted in a gradual decrease in

323   reaction time.

324   Impact of these results on theories of motor planning

325   Reaction time is widely considered an important variable in understanding motor planning, as it

326   is considered that all the processes related to motor planning take place during that interval

327   (Wong et al., 2015; Haith et al., 2016). Indeed, there is a widely accepted hypothesis that motor

328   commands are assembled prior to movement execution during the motor planning stage.

329   However, the present data suggest that this might only be true for pure ballistic movements and

330   reveal a different picture. Incorporating accuracy demands into motor planning seems to be a

331   dynamic process with the amount of accuracy demands taken into account increasing over time.

332   Independently of how loose they are, taking into account accuracy demands imposed a reaction

333   time penalty. This penalty is reduced if the start of the movement consists of a transport phase

334   and therefore the accuracy demands can be incorporated into motor commands later in the

335   movements, hence reducing the cost of accuracy on reaction time.

336   The incorporation of accuracy demands into the control policy can be achieved by the tuning of

337   feedback gains (Todorov and Jordan, 2002; Scott, 2004; Wong et al., 2015), which control the

338   response of the motor system to any perturbations. The tuning of these feedback gains is

339   considered to be achieved at the planning stage for most movements (Nashed et al., 2012;

340   Crevecoeur et al., 2014), but can be performed during the movements if relevant information

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341   has changed (position of the target: Dimitriou et al., 2013; choice of the target, Gallivan et al.,

342   2016b). Here, we provide an example where the motor system deliberately chose to tune the

343   feedback gains later in the movement, even in the absence of any external

344   changes/perturbation.

345   Such specification of motor commands prior to movement onset is also a hallmark of the state-

346   space theory of motor planning where neurons in the motor cortex are thought to reach a given

347   neural state before the movement is actually started (Shenoy et al., 2013; Ames et al., 2014;

348   Kaufman et al., 2014). One can then wonder how the neural state looks like when motor

349   preparation is not complete prior to movement onset but is further refined early during the

350   movement. One prediction is that preparatory activity (in the null space following Kaufman et

351   al., 2014) should be observed during movement execution. Our paradigm can provide

352   information about how delaying the influence of accuracy demands on movement trajectory

353   can influence the neural state of the motor cortex prior to and during movement.

354   Conclusion

355   In this study, we demonstrate that the presence of accuracy demands for reaching movements

356   greatly impacts reaction time. That is, reaction time can be up to 100ms longer in movements

357   for which accuracy demands are immediately taken into account in comparison with

358   movements for which the influence of accuracy demands on movement kinematics is delayed.

359   In contrast to what current theories of motor planning suggest, these results show that

360   movement kinematics can be refined during movement execution in order to reduce reaction

361   time at movement initiation.

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421

422   Legends

423   **Figure 1:** During the line bissection task, participants adopted very different behaviors as illustrated by the hand
424   trajectories from two typical subjects. Participant #19 (panel A) exhibited curved movements for the far targets while
425   participant #12 reached straight to the center of the line for both near and fat targets. For each subject, the starting
426   position is represented by the square and the target lines are represented as black bars. For clarity, the lines are
427   shorter in the illustration than in reality (10, 15 or 20cm). Hand trajectories of all the trials for these participants are
428   given for horizontal lines (blue traces) and for vertical lines (red traces). The distance between the different targets
429   and the starting position are given in panel A. For each subject, the inset in the middle of the figure represents the
430   average vectorial velocity trace (aligned on time of reaching to the target) for horizontal near and far targets (resp.
431   dotted and solid lines). Body midline was aligned with 0 on the horizontal axis.

432   **Figure 2:** Target distance influenced normalized movement curvature (panel A), reaction time (panel B) and
433   movement duration (panel C) for both line orientations. Blue is associated with horizontal lines (H) and red with
434   vertical lines (V). Error bars represent standard error of the mean.

435   **Figure 3:** Target distance influenced the normalized within-subject variability along the movements for both line
436   orientations. Blue is associated with horizontal lines (H) and red with vertical lines (V). Solid lines are associated
437   with the far targets and dotted ones with the near targets. Error bars represent 95% confidence interval.

438   **Figure 4:** Participants who exhibited a larger increase in movement curvature from far to near targets also
439   exhibited a larger decrease in reaction time with target distance. This was true for both line orientations. Left panel
440   is for movements towards horizontal lines and right panel for vertical lines. In each panel, the two points that are
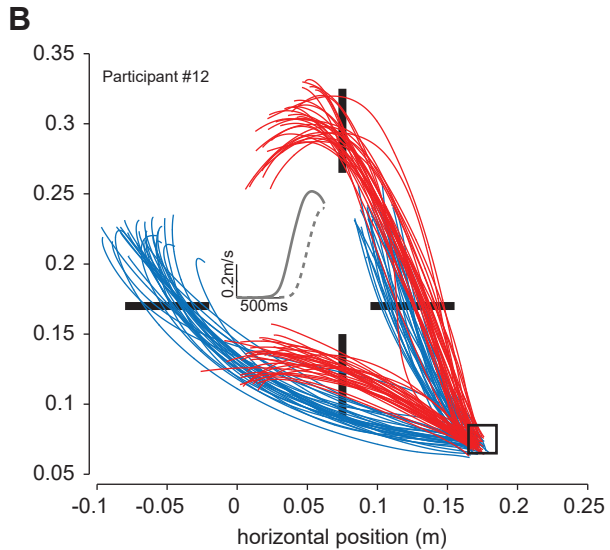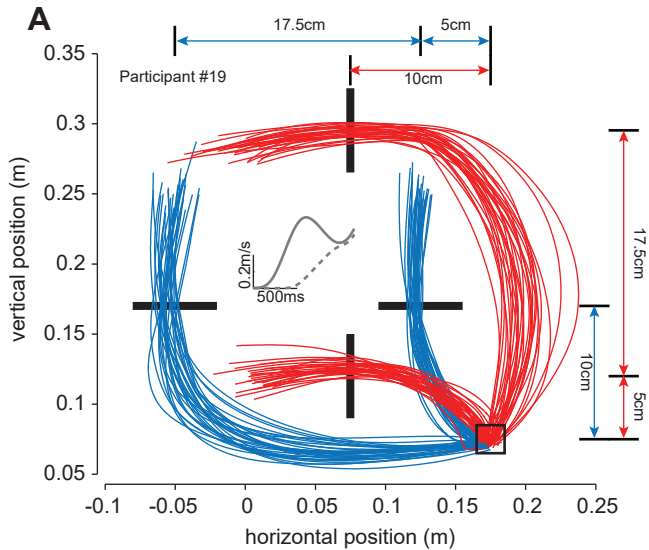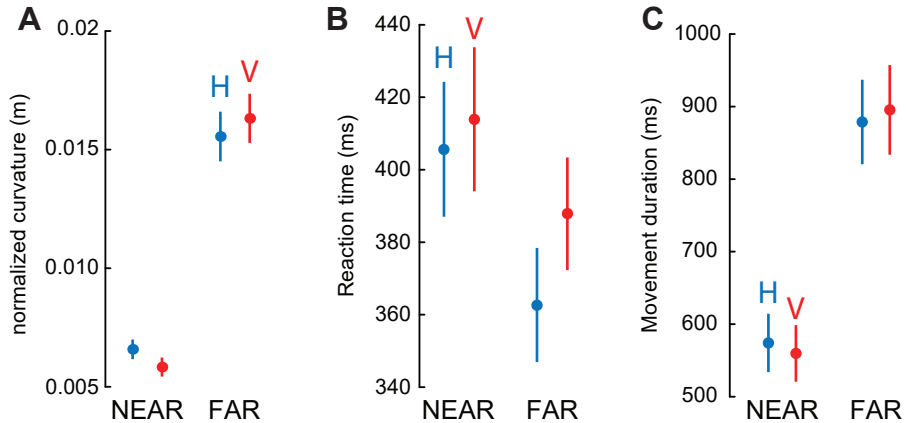441   highlighted (open circles) and numbered correspond to the values for the two subjects illustrated on Fig.1.
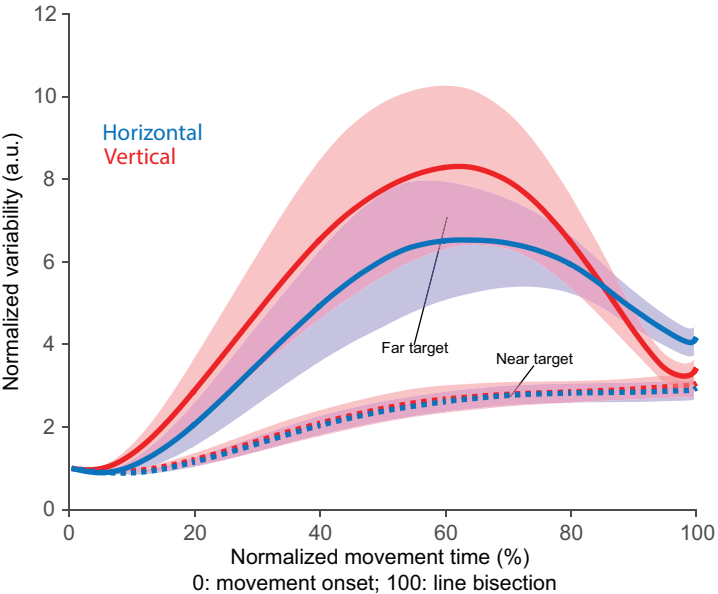
Figure 1

Figure 2

Figure 3

Figure 4