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RESEARCH ARTICLE

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A distance effect in a manual aiming task to remembered targets: a test of three hypotheses

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Abstract It has been noted that manual aiming error and variability when pointing to remembered targets increase as a function of target eccentricity. In the present study we evaluated which one of three hypotheses (target localization, motor, or movement duration) best explains this 'distance effect'. In experiment 1, older and younger participants aimed with their unseen hand at the remembered location of targets distributed between 129 and 309 mm from the starting base. Target presentation time was of either 50 or 500 ms and aiming movements could be initiated following either a 100- or a 10,000-ms recall delay. Participants had either no constraints concerning movement time or were asked to reach the near target in a longer movement time than the farther targets. The results revealed a significant distance effect when no time constraints were imposed but showed a significantly reversed distance effect when the instructions were to reach the near targets in a longer movement time than the far targets. The same results were obtained regardless of target presentation time, recall delay, or age of the participants. These results supported a movement duration interpretation of the distance effect. In experiment 2, a distance effect was replicated when pointing with one's unseen hand toward a remembered target but did not take place when pointing to visible targets. Taken together these results suggest that prolonged movement execution interferes with the stored egocentric target representation.

Keywords Aiming · Reference frame · Memory · Sensorimotor transformations · Aging

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Introduction

Aiming movements toward visual targets are amongst the most frequently performed movements of our repertoire. These movements are performed in a variety of situations. They are most accurate when one's hand is visible throughout the movement toward a visible target (Desmurget et al. 1995; Elliott et al. 1991; Proteau and Cournoyer 1990). They become less accurate when one's hand is not visible during movement execution (Carrozzo et al. 1999; Ghilardi et al. 1995; see also Proteau 1992 for a review), and become even less accurate when the target is no longer visible as movement unfolds (Adamovich et al. 1994; Darling and Miller 1993; Lemay and Proteau 2001; McIntyre et al. 1998; Soechting and Flanders 1989a, b).

Within the latter type of aiming movements, performance is dependent on a host of factors. The objective of the present study was to determine why the spatial error (Adam et al. 1993, 1995; Adamovich et al. 1998, see Fig. 3a visual condition) and/or spatial variability (Lemay and Proteau 1998; Messier and Kalaska 1997; Prablanc et al. 1986) of manual aiming movements to remembered targets increases as a function of an increase in movement amplitude. This decrease in aiming performance as a function of movement amplitude will be referred to as the 'distance effect'. It is important to mention that the distance effect does not simply illustrate the well-known speed–accuracy trade-off that takes place between manual aiming accuracy/variability and movement time (Fitts 1954; Meyer et al. 1982; Schmidt et al. 1979). The effect is observed when participants were asked to reach the target at their own comfortable pace and were allowed to make discrete corrections to their movement until they were confident that it was accurate (Lemay and Proteau 2001). Rather, there are at least three competing hypotheses that are more likely to explain the distance effect. The first hypothesis is motor in nature, the second one is linked to localization and perception of the target, whereas the third is linked to movement duration. In addition, because aging is likely to mediate the distance effect, potential aging effects are considered in the presentation of these hypotheses.

The motor hypothesis

The motor hypothesis is based on the common observation that when participants are asked to aim at the target at their own comfortable pace (Atkeson and Hollerbach 1985; Berthier et al. 1996; Messier and Kalaska 1999) or as quickly and accurately as possible (Gordon et al. 1994a, b), the peak velocity of manual aiming movements increases as a function of movement amplitude. As suggested by Prablanc et al. (1986), because aiming accuracy and variability to a particular target location (i.e., same movement amplitude) are negatively affected by an increase in peak movement velocity (Fitts 1954; Meyer et al. 1982; Schmidt et al. 1979), the distance effect might simply reflect that longer movements are less accurate and/or more variable than shorter ones. However, in contradiction with the motor hypothesis, there is evidence that the variability of movements to remembered targets is not modified by movement velocity (Adamovich et al. 1999), with the exception of movements performed at maximal velocity that were found to be more variable than movements performed at lower velocities (Adamovich et al. 1994).

Concerning the effects of aging, it has been shown that decreasing movement time to a fixed target location resulted in larger increase in error for older than for younger adults (Welford et al. 1969; see also Chaput and Proteau 1996). Considering the observation that aiming peak velocity is larger for farther than for nearer targets, support for the motor hypothesis would be gained if the distance effect was found to be larger for older than for younger adults.

The target localization/perception hypothesis

It has been suggested (Adam et al. 1995; Prablanc et al. 1986) that the distance effect might result from the fact that farther targets are usually detected in the periphery of a visual display and, thus, are not perceived as well as a target located near the center of the same display because: (a) the farther target is seen in visual periphery where the acuity of the visual system concerning the location of objects is relatively weak (Klein and Levi 1987; Westheimer 1982) and (b) the visual saccade required to foveate a farther target is performed at a very high velocity, resulting in an increase in its variability (Abrams et al. 1989). Thus, it could be argued that the poorer localization/perception of farther rather than closer targets might result in larger manual aiming error and variability, causing the distance effect. This explanation holds well for studies in which target presentation time was very short (Adam et al. 1993, 1995; Lemay and Proteau 1998; Prablanc et al. 1986). However, a distance effect was also observed when participants aimed at the remembered location of the target but only after they had had enough time to foveate it prior to movement initiation. Specifically, the target was visible for 2 s in the Adamovich et al. (1998) study and for as long as the participant wanted in the Messier and Kalaska (1997, task 1) study. Although the results of the last two studies argue against a target localization/perception explanation of the distance effect, it might be that the effect is mediated by a target localization/perception factor and that it would increase when the time allowed to participants to foveate the target decreases.

It has been shown that aging results in an increase in the time required to initiate a visual saccade toward a visual target by up to 100 ms (Morrow and Sharpe 1993; Moschner and Baloh 1994; Munoz et al. 1998; Pratt et al. 1997; Warabi et al. 1986). In addition, Moshner and Baloh (1994) have shown that peak saccade velocity to a target located at 30° of visual angle from a fixation point was decreased by as much as 71°/s for older participants in comparison to younger adults (see also Morrow and Sharpe 1993; Munoz et al. 1998 for similar results). Both these effects of aging on the performance of ocular saccades suggest that target foveation is longer in older than in younger adults. Thus, if the distance effect is caused by target localization/perception, the presentation of the target for a short period of time should result in a larger distance effect for older than for younger participants.

The movement duration hypothesis

Pointing with one's unseen hand to a remembered target requires that information about target information and initial arm position be translated into appropriate motor commands. In such a condition, recent observations reported by McIntyre et al. (1998) (see also Carrozzo et al. 1999; Soechting and Flanders 1989a, b) suggest that the target location would be first encoded in a viewer-centered frame of reference (based on retinal and extraretinal cues) and then transformed into a body-centered frame of reference (arm or shoulder-centered; however see also, Chieffi et al. 1999; Vindras and Viviani 1998 for evidence of a hand-centered frame of reference).

Depending on the delay between disappearance of the target and movement completion, the stored location of the target might be available through different memory systems. When this delay is short (in the order of 1 s), target location might be available in a brief duration sensory memory store, such as iconic memory (Adam et al. 1995; Elliott and Calvert 1992; Elliott and Madalena 1987; Hanari 1996; Lemay and Proteau 2001). In this situation, it is plausible that the target is available in an egocentric/viewer-centered frame of reference. This frame of reference would combine retinal and extraretinal cues because the participant still has access to a visual representation of the target as was shown by Sperling (1960). When longer delays elapse between target disappearance and movement completion, because the information available in iconic memory decays rapidly, it is likely that the location of the target used for movement planning and control is based on its representation in the visuospatial sketchpad (Baddeley and Hitch 1974; Logie 1995), a more durable memory, which codes the location of the target in a body-centered frame of reference (hand-centered, Chieffi et al. 1999). The larger errors found for farther than for nearer targets might result from this putative transition from a viewer-centered to a body-centered frame of reference (see McIntyre et al. 1998 for confirming evidence), or by the simple passage of time as movement unfolds.

According to the movement duration hypothesis, aging should not modify the distance effect. This is so because Lemay and Proteau (2001) recently showed that older participants performed manual aiming movements to remembered targets as accurately and with no more variability than younger participants for both short (100 ms) and long recall delays (10,000 ms).

Experiment 1

The first goal of the present study was to determine which one of the three hypotheses reviewed above better explains the distance effect. To reach our goal we had participants aim at remembered targets. For a first group (hereafter called 'the control group'), the instructions were to aim at the target at a comfortable pace. We were expecting to observe longer movement times and higher peak movement velocities for farther than for nearer targets (Atkeson and Hollerbach 1985; Gordon et al. 1994a, b; Messier and Kalaska 1999). For a second group (hereafter called 'the experimental group'), participants were asked to reach the nearer targets in a relatively long predetermined movement time bandwidth (between 2 and 5 s) but to reach the farther targets in a relatively short movement time (1 s).

If the distance effect is caused only by a target localization/perceptual factor, because the instruction given to the experimental group could not have any effect on target perception, we should observe a distance effect for both the control and the experimental groups. If motor processes cause the distance effect, asking participants in the experimental group to reach the farther targets in a shorter movement time than the nearer targets should increase peak velocity for the farther targets in comparison to the control group and result in a larger distance effect for the experimental than for the control group. However, if the movement duration hypothesis better explains the distance effect, this effect should be observed for the control group but *reversed* for the experimental group because the nearer targets are reached in a longer movement time than the farther targets.

We also manipulated the delay between target disappearance and movement initiation (i.e., a recall delay) and the time for which the target was visible. We used short (100 ms) and long (10,000 ms) recall delays to determine whether the distance effect is mainly caused by the passage of time or whether it is linked with movement duration as suggested by the movement duration hypothesis. If the distance effect is caused by the passage of time between target disappearance and movement completion, aiming performance, at least for the control group, should suffer more from an increase of the recall delay from 100 to 10,000 ms than from an increase in movement duration. Alternatively, if it is movement duration per se that causes the distance effect, an increase in movement duration would be more detrimental to aiming performance than an increase in the recall delay.

Increasing target presentation time increases the likelihood that target foveation be completed before the target has been extinguished. Thus, if target localization processes cause the distance effect, it should be smaller for the longer than for the shorter target presentation time. Also, because target presentation time does not influence movement time or movement peak velocity (Lemay and Proteau 2001), increasing target presentation time should not influence the distance effect if either motor processes or movement duration cause this effect.

Finally, we wanted to determine whether aging would influence the distance effect. As proposed above, the motor and target localization hypotheses suggest a larger distance effect for older than for younger participants whereas the movement duration hypothesis does not suggest any modulation of this effect by age.

Materials and methods

Participants

Twenty younger adults (mean 22.7 years, SD 3.49 years) and 20 older adults (mean 70.55 years, SD 4.64 years) took part in this study. All participants were self-declared right handed, had good upper limb mobility, and did not have any visual deficit except those corrected by prescription lenses. The younger participants were all students in the Département de kinésiologie at the Université de Montréal. All older participants lived in their own residences and reported being in good health. Participants, were paid for their time and were unaware of the purpose of the study. All participants gave their informed consent prior the beginning of the experiment. This experiment has been approved by the local ethics committee.

Tasks and apparatus

Participants aimed at one of nine possible targets presented on a computer screen (Mitsubishi Color Diamond Pro, 37 inches equipped with a Matrox Millennium II video card having a resolution of 1,024×768 pixels). Specifically, participants held a pointer with their thumb and index finger and moved it on a near frictionless track located in front of the computer screen and parallel to it. The track was located 50 mm in front of the screen (see Fig. 1) and was located 1 cm below the lower extremity of the target. The task was very much like dragging one's finger on the screen from a fixed starting position to a target shown on the screen, however without touching it. A cardboard shield prevented the participants from viewing their upper limb or their pointer. All targets were white (on a black background), with a width of 3.2 mm and a height of 64.5 mm (sustaining a visual angle of 0.366° and 7.35°, respectively). The distance between the participant and the computer screen was 500 mm. The distance between each target was 22.5 mm. They were located at a minimum of 129 mm and at a maximum of 309 mm from a fixed starting base aligned with the left edge of the computer screen.

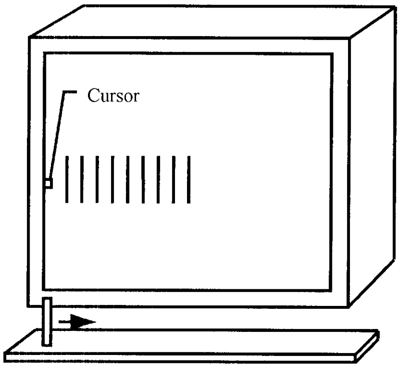

Fig. 1 Sketch of the apparatus. Pointer is seen on the starting position. All possible target locations are illustrated

The pointer was connected to an optical encoder (US Digital, model S2–1024-NT, sampling rate of 500 Hz, spatial precision of 0.17 mm), sampled by a microcomputer. For the whole experiment, participants wore liquid crystal goggles (Plato Translucent Technologies), which changed from a transparent to a translucent state immediately after the presentation of the target, thus instantaneously (~3 ms) depriving participants of visual contact of the target and the apparatus in general.

Procedure

Participants sat in front of the computer screen. They were asked to gaze at the screen before the beginning of each trial. We did not use a fixation point to prevent the possibility that visual persistence of this point could be confounded with that of the target. At the beginning of each trial, the participant had to hold the pointer between the thumb and the index finger of his or her non-dominant hand. Once the pointer was stabilized at the starting position, the target was presented on the computer screen and remained visible for either 50 or 500 ms. The target and all other visual cues disappeared from view when the goggles' lenses went from their transparent to their translucent state. Once the goggles were set in their translucent state, the participant was to wait for a delay of either 100 or 10,000 ms before initiating his or her movement toward the target. An auditory stimulus indicated when movement could start. The beginning of the pointing movement was defined as the moment at which the velocity of the pointer exceeded 3 cm/s whereas the end of the movement occurred when the velocity of the pointer decreased below 3 cm/s for at least 1,000 ms. This procedure allowed participants to correct their movement if they so desired.

The experiment began with a practice block of eight trials performed in normal vision (without goggles) and was followed by a second practice block of eight trials performed with the goggles in their translucent state. The objective of the first block of practice was to familiarize participants with the pointing task, whereas the second block of practice was used to familiarize participants with the experimental procedures. For the control groups (one in each age group), participants were asked to reach the location of the target as accurately as possible and with no temporal constraints. For the experimental groups (again, one in each age group), participants were asked to complete their reaching movement in a movement time of between 2 and 5 s for the four targets nearer to the starting base, and in a movement time of approximately 1 s for the four targets located farther from the starting base. The middle target had to be reached in a movement time ranging between 2 and 5 s for one half of the trials and in a movement time of approximately 1 s for the other half of the trials (the data collected for this target were not analyzed). The order of presentation of the two imposed movement times was randomized for each participant. Relatively long movement times were used for the nearer targets because we wanted to make sure that all movements to the nearer targets would take longer than all movements to the farther targets. For each block of practice, four trials were carried out for each one of four target presentation times. For each of these four trials, the targets were visible for 500 ms for the first trial and then the presentation time decreased to 300, 150, and 50 ms for the next trials of practice. Practice trials were carried out on targets located at intermediate positions compared to the targets used in the experimental phase. During this practice phase, participants were informed of the spatial accuracy of their movement in cm (for example, "your movement ended 2 cm short of the target").

Following the practice phase, the participants performed 72 experimental trials. These trials were presented in four successive blocks (two target presentation times × two recall delays) of 18 trials each. The order of presentation of the different blocks was randomized across participants. In each experimental block of trials, the participants carried out two trials toward each of the nine possible targets. The order of presentation of the targets was randomized within each block with the restriction that each target was presented once in each successive series of nine trials. Participants in the experimental group were informed prior to each trial of the target movement time for the upcoming trial. During both the practice and the experimental phases, trials for which the participants did not complete their movement within the imposed time bandwidth were repeated. An experimental session lasted approximately 30 min.

Dependent variables

The main dependent variables of the present study were the absolute constant error and the variable error of aiming. The first one is the absolute value of the mean aiming error found for each participant. It was favored over the constant error of aiming (signed mean aiming error), which is used to determine whether aiming movements show a bias (undershooting or overshooting of the target), because none of the hypotheses reviewed in the Introduction to explain the distance effect predicts a particular aiming bias. The variable error of aiming is the within-participant standard deviation of the individual movement endpoints. In addition, because the motor hypothesis predicts that aiming performance would be related to it, we also analyzed the peak velocity of the aiming movement. To this end, the displacement data of the cursor over time were first smoothed using a fourth order recursive Butterworth filter with a cut-off frequency of 10 Hz. The smoothed data were then numerically differentiated once using a central finite technique to obtain the velocity profile of the aiming movement. Movement peak velocity was determined from this profile with an interactive software program. Movement initiation was defined as the moment at which the velocity of the pointer exceeded 3 cm/s whereas movement completion occurred when the velocity of the pointer decreased below 3 cm/s for at least 1,000 ms.

Statistical analyses

To reach our first goal the data of the absolute constant error, of the variable error, and of the movement peak velocity were submitted to a 2×2×2×2×2 MANOVA using repeated measurements on the last three factors. The first factor corresponded to the two groups (experimental vs control). The second factor corresponded to the two age groups used in the present study (younger vs older adults). The third factor was the target presentation time (50 vs 500 ms). The fourth factor was the delay between occlusion of the target and movement initiation (i.e., recall delay:100 vs 10,000 ms), and the last factor concerned the target location. The results obtained for the three nearer and for the three farther targets in relation to the starting base were regrouped into two clusters (near targets vs far targets). Significant effects ($P<0.05$) were broken down by computing separate ANOVAs for each dependent variable. In all cases, significant interactions were further delineated using the Newman-Keuls technique ($P<0.05$), corrected for the number of pairwise comparisons using the Bonferroni technique.

Table 1 Mean (and SD) of movement time, absolute constant error, variable error, and movement peak velocity as a function of group, recall delay (100 or 10,000 ms), and target location (near or far) for a target presentation time of 50 ms. Experiment 1

Groups		100 ms		10,000 ms	
		Near	Far	Near	Far
		Movement time (ms)			
Younger adult	Control	1031 (462)	1343 (529)	1059 (398)	1464 (589)
	Experimental	3085 (559)	823 (123)	2999 (682)	899 (203)
Older adult	Control	954 (307)	1234 (375)	1135 (515)	1428 (571)
	Experimental	3066 (679)	950 (211)	3365 (615)	953 (130)
		Absolute constant error (mm)			
Younger adult	Control	17.2 (16.6)	25.6 (15.4)	34.4 (26.6)	41.5 (23.2)
	Experimental	43.6 (15.8)	36.7 (27.4)	40.9 (26)	24.6 (11.2)
Older adult	Control	33.7 (24)	62.1 (42.1)	40.3 (31.3)	50.5 (46.9)
	Experimental	43.5 (19.2)	35.4 (26.7)	54.7 (32.9)	52.5 (30.4)
		Variable error (mm)			
Younger adult	Control	19.9 (6.3)	29.5 (15.2)	22.9 (8.7)	33.3 (15.1)
	Experimental	31.9 (13.2)	19.1 (10.2)	33.2 (20.2)	21.5 (6.2)
Older adult	Control	23.3 (8.4)	27.5 (14.8)	26.4 (11)	38.5 (25.8)
	Experimental	27.6 (8.6)	21.7 (9.8)	37.8 (21.9)	24.8 (10)
		Movement peak velocity (mm/s)			
Younger adult	Control	278 (121)	442 (177)	195 (84)	373 (138)
	Experimental	73 (14)	827 (248)	84 (40)	773 (247)
Older adult	Control	302 (98)	511 (154)	243 (72)	417 (144)
	Experimental	81 (27)	675 (194)	79 (33)	652 (197)

Table 2 Mean (and SD) of movement time, absolute constant error, variable error, and movement peak velocity as a function of group, recall delay (100 or 10,000 ms), and target location (near or far) for a target presentation time of 500 ms. Experiment 1

Groups		100 ms		10,000 ms	
		Near	Far	Near	Far
		Movement time (ms)			
Younger adult	Control	1067 (338)	1334 (430)	1208 (405)	1495 (568)
	Experimental	3141 (444)	824 (102)	2948 (469)	831 (98)
Older adult	Control	1009 (211)	1208 (266)	1144 (307)	1398 (379)
	Experimental	3053 (839)	950 (177)	3227 (953)	919 (123)
		Absolute constant error (mm)			
Younger adult	Control	16.8 (18.7)	20.8 (16.3)	22.7 (20.3)	43 (36.1)
	Experimental	34.4 (14.2)	23.7 (10.7)	(21.1)	(14)
Older adult	Control	34 (23.5)	53 (33.3)	29.2 (22.4)	48.5 (34.6)
	Experimental	41.7 (22.8)	39.3 (41)	52.4 (33.3)	48.1 (38)
		Variable error (mm)			
Younger adult	Control	19.1 (7.1)	21 (10.1)	21.3 (7)	27.4 (10.8)
	Experimental	29.2 (12)	14.9 (5.5)	37.7 (12.1)	19.6 (8.5)
Older adult	Control	18.7 (10.5)	26.3 (21.3)	24.5 (8.8)	20.8 (4.8)
	Experimental	26 (10.1)	20.3 (8.6)	35.1 (31.7)	21.3 (7.2)
		Movement peak velocity (mm/s)			
Younger adult	Control	238 (101)	418 (145)	194 (85)	324 (139)
	Experimental	80 (18)	809 (253)	76 (21)	791 (253)
Older adult	Control	271 (68)	495 (129)	238 (80)	422 (104)
	Experimental	84 (29)	633 (161)	87 (26)	637 (215)

Results

The mean data (and standard deviation) obtained for all dependent and independent variables of the present experiment are presented in Tables 1 and 2.

Movement time

As illustrated in Fig. 2 (*upper left panel*), participants in the experimental group completed their movement to the near and far targets within the prescribed movement time bandwidth whereas, as expected, participants in the control group reached the near targets in a shorter movement

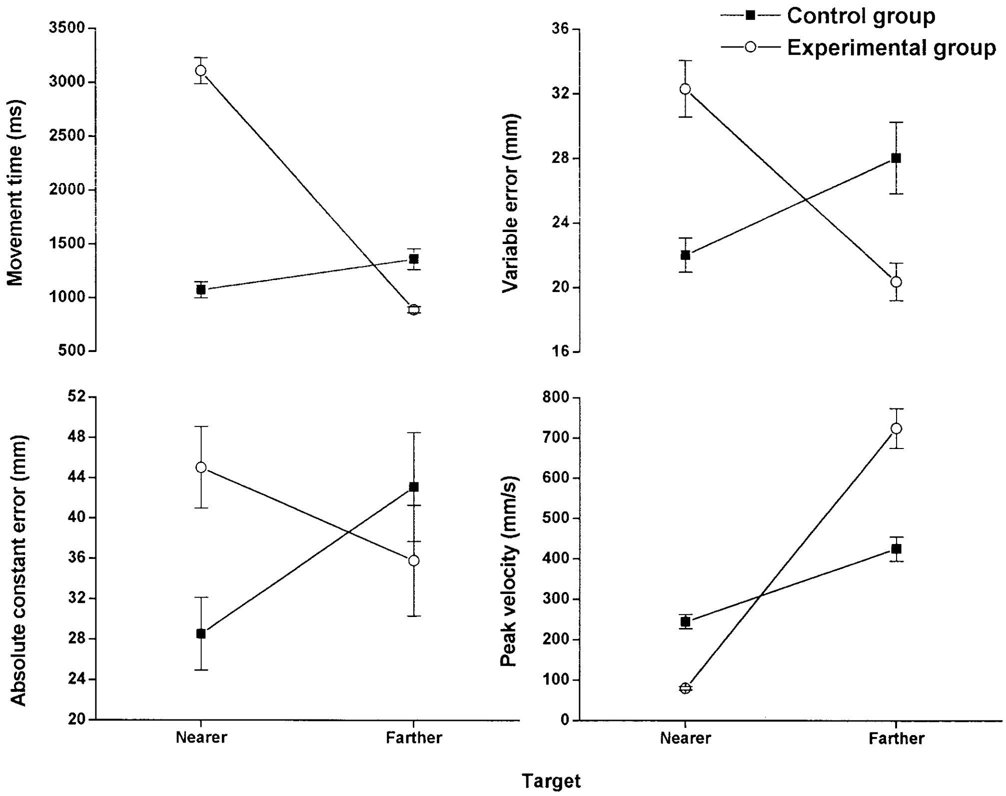

Fig. 2 Mean results of experiment 1. Participants of the experimental group completed their movement within the allowed movement time and movement time was longer for the farther than for the nearer targets for the control group (*upper left panel*). Results of the absolute constant error (*lower left panel*) and of the variable error (*upper right panel*) of aiming show a significant distance effect for the control group and a significant but reversed distance effect for the experimental group. Peak movement velocity (*lower right panel*) was higher for the farther than for the nearer targets and more so for the experimental than for the control group

time than the far targets. An ANOVA contrasting the five independent variables manipulated in the present study only revealed a significant Group × Target interaction, $F(1,36)=412.34$, supporting the above observation.

The MANOVA computed on the three dependent variables revealed significant main effects of target, of target presentation time, and of the recall delay, *Rao's* $R(3,34)=92.93$, 4.19, and 11.29, respectively. In addition, the MANOVA revealed a significant Group × Target interaction as well as a significant Group × Recall delay interaction, *Rao's* $R(3,34)=50.72$ and 3.90, respectively.

Absolute constant error of aiming

The Group × Target interaction was significant for this dependent variable, $F(1,36)=17.81$. It is illustrated in Fig. 2 (*lower left panel*). The breakdown of this interaction revealed a significant distance effect for the control group, that is, a larger aiming error for the farther than for the nearer targets, and a significant but *reversed* distance effect for the experimental group, indicating a larger aiming error for the nearer than for the farther targets. The main effect of the recall delay, $F(1,36)=4.8$, was also significant, indicating a larger error for the 10,000-ms recall delay than for the 100-ms recall delay (41.2 vs 35 mm). For the control group, its worth noting that the passage of time per se (10,000-ms recall delay minus 100-ms recall delay) resulted in an increase in error of approximately 5.9 mm whereas, regardless of the recall delay, there was an increase in error of approximately 15 mm when going from the near to the far targets. Finally, it is worth noting that the constant error (signed error) showed that the control group undershot both the near and the far targets (–8.4 vs –3.2 mm, respectively) whereas the experimental group undershot the near targets (–19.2 mm) but overshot the far targets (12.5 mm).

Variable error of aiming

Again, the Group × Target interaction was significant for this dependent variable, $F(1,36)=59.31$. Its breakdown revealed a significant distance effect for the control group (larger variable error for the farther than for the nearer targets) and a significant but *reversed* distance effect for the experimental group (see Fig. 2 *upper right panel*). Main effects of the target presentation time, $F(1,36)=5.93$, and of the recall delay, $F(1,36)=9.24$, were also significant. The first effect indicated a larger variable error for the shorter than for the longer target presentation time (27.4 vs 24.0 mm), suggesting that increasing target presentation time permitted a better perception of target location. The second effect revealed a larger variable error for the longer than for the shorter recall delays (27.9 vs 23.5 mm). This indicated that the information stored in memory concerning target location became less reliable as time went by (Carrozzo et al. 1999; Chieffi et al. 1999; Elliott and Madalena 1987). However, for the control group and regardless of the recall delay, the simple passage of time had a smaller effect on variable error (3.6 mm) than movement duration (5.85 mm).

Movement peak velocity

The Group × Target interaction was also significant for this dependent variable, $F(1,36)=85.69$. This interaction is illustrated in Fig. 2 (*lower right panel*). Its breakdown indicated that for both the control and the experimental groups, peak velocity was significantly higher for the farther than for the nearer targets. However, this increase in peak velocity was significantly more pronounced for the experimental than for the control group. This interaction was to be expected considering the movement time target bandwidth used for the experimental group. The Group × Recall delay interaction was also significant, $F(1,36)=10.74$. Its breakdown revealed for the control group a significantly higher peak velocity for the shorter than for the longer recall delay (370 vs 301 mm/s). No effect of the recall delay was observed for the experimental group (401 and 397 mm/s, respectively). The higher velocity found for the control group for the 100 ms recall delay suggests that participants might have increased the velocity of their movement to benefit from the information available in iconic memory to control their ongoing movement (see Lemay and Proteau 2001 for similar findings). However, it is likely that the instruction given to the experimental group concerning movement time homogenized the aiming movements, which would explain why the recall delay did not influence peak velocity for this group. Finally, peak velocity was higher for the shorter (375 mm/s) than for the longer target presentation time (362 mm/s), $F(1,36)=4.56$.

Discussion

The major goal of this experiment was to determine which one of a target localization, a motor, or a movement duration hypothesis better explains why aiming performance to remembered targets has been found to be a function of movement amplitude. The first major observation of the present study was that the distance effect was replicated for the control group because both the absolute constant error and the variable error of pointing were larger for the farther than for the nearer targets.

If the distance effect is caused by poor target localization/perception, the distance effect should have taken place for both the control and the experimental groups, but non-existent, or at least less pronounced, for a condition permitting better perception of the target. Increasing target presentation time from 50 to 500 ms resulted in a significant decrease in variable error of aiming suggesting that, indeed, it permitted better perception of the target (Adam et al. 1995; Lemay and Proteau 2001). However, increasing target presentation time did not modify the distance effect. The above finding, the reversal of the distance effect for the experimental group, and previous results indicating the presence of a distance effect even when long target presentation times were used (Adamovich et al. 1998; Messier and Kalaska 1997) indicate that a target localization explanation of the distance effect is not viable, neither as the main contributor nor as a modulator of the distance effect.

The motor explanation of the distance effect suggested that it resulted from higher peak velocities for aiming movements to farther rather than to nearer targets which, in turn, would have resulted in larger aiming error and variability. Considering that the farther targets were reached with a higher peak aiming velocity for the experimental than for the control group, this hypothesis would have been supported if a larger distance effect had been observed for the experimental than for the control group. This was clearly not the case. In fact, the results showed just the opposite.

The results suggest rather, that the distance effect is caused by movement duration. Numerous aspects of the results support this position. The first and most convincing support for our conclusion is that the distance effect was significantly reversed when participants were asked to reach the nearer targets in a shorter movement time than the farther targets. The fact that larger pointing error and variability were found for the experimental group for movements of small amplitude (i.e., the nearer targets) that were reached in a long movement time indicated that it is movement duration not movement amplitude that causes the distance effect. The second line of evidence supporting the movement duration hypothesis comes from the observation that the difference in aiming accuracy and variability between the control and the experimental groups was larger for the nearer than for the farther targets (see Fig. 2). This observation fits well with the movement duration hypothesis because the difference in movement time between the two groups was much larger for the nearer than for the farther targets. Note that this observation is opposite to what should have been observed according to the motor hypothesis whereas no difference should have been observed according to the target localization hypothesis. The last line of support comes from the fact that older participants behave exactly as their younger counterparts. This result supports the movement duration hypothesis because Lemay and Proteau (2001) recently showed that older and younger adults were similarly affected by an increase of the recall delay. Taken together, the results of the present study and those of Lemay and Proteau (2001) suggest that older adults are as capable as younger ones of retaining target location in memory. However, because this last line of support for the movement duration hypothesis is based on an absence of difference between the two age groups, it should be considered with more caution.

The results also gave indication that the distance effect is not caused by the passage of time per se but that it is related to the duration of the ongoing movement. This position is supported by the observation that for the control group an increase in movement duration of approximately 300 ms when going from the near to the far targets resulted in nearly twice the increase in absolute constant error and variable error than that noted between recall delays of 100 and 10,000 ms. This observation is important. It suggests that movement execution might interfere with the maintenance of target location in memory.

Finally, there was one aspect of the results of the present experiment that was unexpected. Considering that older participants had been shown to need more time than younger adults to foveate a target suddenly presented on a visual display (Morrow and Sharpe 1993; Moschner and Baloh 1994; Munoz et al. 1998; Pratt et al. 1997; Warabi et al. 1986), it was somewhat surprising that aiming performance was not affected by aging, especially for the shorter target presentation time. However, it should be remembered that we did not use a visual fixation point in the present study because it could have interfered with storage of the target location in memory. Thus, it is likely that the participants' gaze was directed near the middle of the visual display. By doing so, the extreme targets were located at 10.2° of visual angle relative to the center of the display, that is, in central vision, which might have reduced the difference in the time required to foveate the target between younger and older participants to a negligible delay.

Experiment 2

One goal of the present experiment was to ascertain whether the distance effect occurs because movement execution interferes with the stored location of the target in memory. This proposition would be supported if a significantly larger distance effect was observed when pointing toward remembered targets than when pointing toward visible targets. Although there is some evidence available to that effect (Prablanc et al. 1986), some confirmation is warranted. Because target presentation times, recall delay, and age of the participants did not modulate the distance effect in experiment 1, these factors were not included in the present experiment.

Materials and methods

Participants

Ten students in the Département de kinésiologie at the Université de Montréal, none of whom had participated in experiment 1, took part in this experiment, (mean 26.7 years, SD 8.27 years). All participants were self-declared right handed, were paid for their time, and were unaware of the purpose of the study. All participants gave their informed consent prior the beginning of the experiment. This experiment has been approved by the local ethics committee.

Task, apparatus, and procedures

The task and apparatus were similar to those used in experiment 1. The procedures were also similar to those used in experiment 1 for the control group (i.e., no time constraints) but with a few exceptions. Participants completed 99 trials to remembered targets and also 99 trials to visible targets. The order of presentation of these two conditions of target visibility was counterbalanced across participants. When the target was not visible during movement execution, target presentation time was of 500 ms and the recall delay was of 100 ms for all trials. For both conditions of target visibility, the first 9 trials (1 trial per target) were considered as familiarization. Participants were informed of the accuracy of their movement following each one of these trials. For the remaining 90 trials, the order of presentation of the different targets was randomized with the restriction that each target was used once in every successive block of 9 trials. No knowledge of results was provided for these trials.

Dependent variables and statistical analyses

The dependent variables were the movement time, the absolute constant error of aiming, the variable error of aiming, and the movement peak velocity. They were submitted to a 2×2 MANOVA using repeated measurements on the two factors. The first factor was the condition of target visibility (visible vs not visible), whereas the second factor concerned the target location, as defined in experiment 1. The results of the MANOVA were broken down as described in experiment 1. Data from one participant were withdrawn from all analyses because his or her results concerning the variable error of aiming differed by more than two standard deviations from the group mean.

Results

The mean data (and standard deviation) obtained for all dependent and independent variables of the present experiment are presented in Table 3.

The results of the MANOVA revealed significant main effects of Target visibility and of Target location, as well as a significant interaction between these two factors, *Rao's* $R(4,5)=6.6$, 66.0, and 4.8 ($P=0.055$), respectively. None of these effects were found significant for the absolute constant error of aiming. However, as illustrated in Fig. 3 (*lower panel*) when the target was visible, aiming error was somewhat smaller for the far than for the near targets. The opposite was observed when the target was not visible. Also, the constant error data showed that near targets were undershot whereas far targets were slightly overshot (–13.8 vs 4.7 mm).

Movement time

The ANOVA revealed that participants needed more time to complete their aiming movement for the far than

Table 3 Mean (and SD) of variable error, absolute constant error, movement time, and movement peak velocity as a function of target visibility and of target location. Experiment 2

Target	Near	Far
	Variable error (mm)	
Visible	19.4 (2.9)	18.9 (4.7)
Remembered	18.4 (2.9)	24.2 (6.5)
	Absolute constant error (mm)	
Visible	20.3 (13.4)	15.6 (12.1)
Remembered	19.2 (18.4)	19.6 (15.2)
	Movement time (ms)	
Visible	1567 (387)	1986 (469)
Remembered	1372 (421)	1725 (526)
	Movement peak velocity (mm/s)	
Visible	177 (55)	307 (93)
Remembered	235 (93)	359 (134)

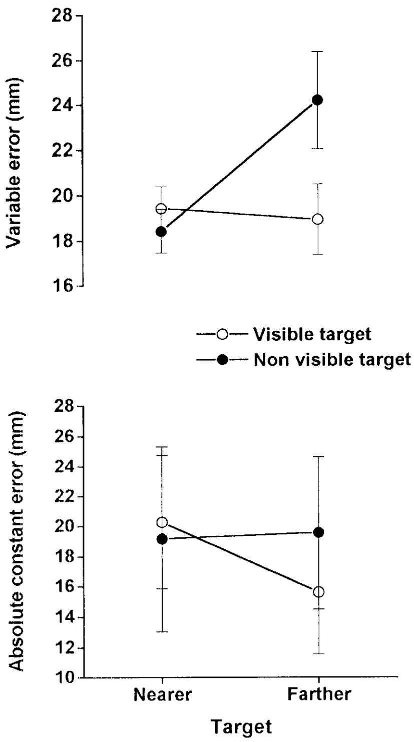

Fig. 3 Mean results of experiment 2. Results of the variable error of aiming (*lower panel*) show a significant distance effect when pointing to remembered targets but not when pointing to visible targets. The absolute constant error of aiming (*upper panel*) was not modified by either target location or target visibility

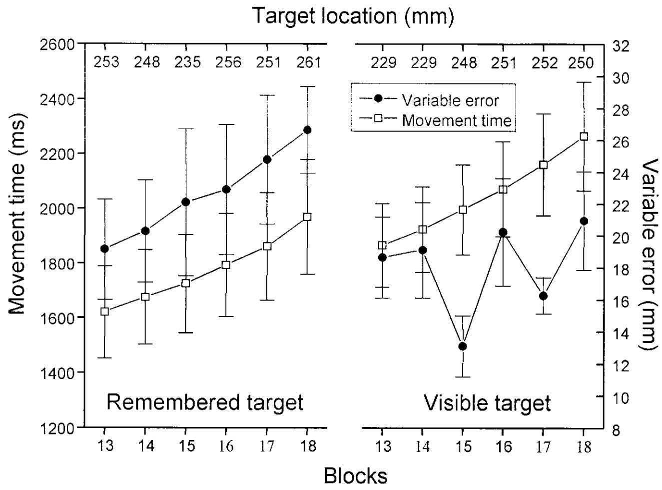

Fig. 4 Variations in movement time (*left axis, open markers*) and in the variable error of aiming (*right axis, filled markers*) when pointing to remembered targets (*left panel*) and to visible targets (*right panel*). The *lower ordinate* refers to block number when trials were ranked from the slowest to the fastest (block 18). The *upper ordinate* indicates mean target location for each block of trials. Note that, when pointing to remembered targets located approximately at the same distance from the starting base, the variable error of aiming increases as a function of movement duration. No such trend is apparent when pointing to visible targets

for the near targets, $F(1,8)=41.89$. In addition, movement time was significantly longer when the target was visible than when it was not, $F(1,8)=11.11$. The data of interest are presented in Table 3.

Variable error

The ANOVA revealed a significant main effect of Target, $F(1,8)=7.59$ as well as a significant Target × Target visibility interaction, $F(1,8)=8.06$. This interaction is illustrated in the *upper panel* of Fig. 3. Its breakdown showed that a significant distance effect took place when the target was not visible; variable error was significantly larger for the far rather than for the near targets. Alternatively, when the target was visible, variable error is slightly smaller (not significant) for the far than for the near targets. This trend is opposite to the distance effect.

Movement peak velocity

The ANOVA revealed significant main effects of Target visibility and of Target location, $F(1,8)=8.47$ and 57.5, respectively. The first effect indicated a higher peak velocity when aiming at remembered rather than at visible targets whereas the second effect indicated a higher peak velocity for the far than for the near targets. The results of interest are presented in Table 3.

Supplementary analyses

The results of both experiment 1 and the present experiment suggest that the distance effect is caused by the decay of the remembered target representation as a function of movement duration. If this is the case, longer movement times to similar target locations should have resulted in an increase in pointing variability, and perhaps also in pointing accuracy, in comparison to shorter movement times. To test this prediction, we ordered the movement times of each participant from the shortest to the longest. Movement times and their corresponding target location were averaged over 18 blocks of five trials each. A variable error and an absolute constant error of aiming were then computed for each block. For the first 12 blocks, there was a concomitant increase in movement time and mean target distance (Pearson's coefficient of correlation = 0.98). Thus, it could not be determined whether an eventual increase in pointing error and/or variability was linked to movement distance or to movement duration. However, for the 6 blocks associated with the longer movement times, participants aimed approximately at the same target location (fluctuated between 235 and 261 mm) but in different movement times (Pearson's coefficient of correlation = 0.51). The results of interest are presented in Fig. 4. For the participants who aimed at a remembered target location, an increase in movement time from 1,621 to 1,968 ms resulted in gradual increase in pointing variability going from 19.1 to 26.6 mm (Pearson's coefficient of correlation = 0.99), whereas no such gradual increase in pointing variability as a function of an increase in movement time was observed for participants who aimed at visible targets (Pearson's coefficient of correlation = 0.22). The absolute constant error did not fluctuate as a function of movement time, regardless of whether or not the target was visible.

Discussion

The results of the present experiment are straightforward. A distance effect was obtained for the variable error when aiming to remembered targets whereas this was not the case when the targets were visible. The lack of significant difference in aiming accuracy and variability between the near and the far targets when the target was visible cannot be accounted for by a lack of statistical power in the present experiment. First of all our conclusion is based on a significant interaction. Secondly, when the targets were visible, aiming performance to the farther targets tended to be better, not poorer, than that to the nearer targets.

The most important aspect of these results is that the distance effect found in experiment 1 for a short recall delay was replicated, although only for the variable error of aiming. Finding a distance effect when pointing to remembered targets and not when pointing to visible targets indicates that the distance effect has to do with the keeping of the target location in memory. Further, the results of the supplementary analysis supported our proposition that the distance effect is related to movement duration, not movement extent. Finally, contrary to experiment 1, we did not find a distance effect for the absolute constant error of aiming. A possible explanation of these conflicting results might be that, for the combination of target presentation time and recall delay used in experiment 2, a ceiling had been reached for this dependent variable. Specifically, in experiment 2, mean movement time to the near remembered target was of 1,372 ms for an absolute constant error of 19.2 mm. For the same experimental condition in experiment 1 (young participants, target presentation time of 500 ms, and recall delay of 100 ms) mean movement time was of 1,334 ms *but for the farther targets*. It resulted in a mean absolute constant error of 20.8 mm. Thus it might be that the absolute constant error had reached a ceiling at a movement time of approximately 1,400 ms, and would explain why absolute constant error did not show a distance effect in experiment 2. This interpretation of the conflicting results is speculative but coherent with previous propositions suggesting that variable error and constant error do not provide a window on the same processes (Carrozzo et al. 1999; Guay 1986; Guay and Hall 1984; McIntyre et al. 1997; Soechting and Flanders 1989a, b).

General discussion

The main goal of the present study was to determine which of a target localization/perception, a motor, or a movement duration hypothesis better explains the observation that pointing movements to remembered targets are less accurate and more variable with an increase in movement amplitude. The results of experiment 1 supported previous observations suggesting that the target localization (Adamovich et al. 1998; Messier and Kalaska 1997) and the motor (Adamovich et al. 1994, 1999) explanations of the distance effect were unlikely, but supported a movement duration interpretation of this effect. Further, the fact that we found a distance effect after both short and long recall delays suggests that it has a single cause, regardless of the recall delays used in the present study.

The distance effect

As indicated above, a distance effect took place when pointing to remembered targets, regardless of the recall delay, but did not take place when the target remained visible throughout movement execution. This pattern of results clearly indicates that the distance effect is related to the storage/recoding of target location in memory. Although the distance effect is related to target storage, this effect clearly does not result from the simple passage of time as movement progresses from near to far targets. This position is supported by what is perhaps the most striking result of the present study. In experiment 1, the 300-ms increase in movement time noted when going from the near to the far targets had deleterious effects on aiming performance, after both a 100- or 10,000-ms recall delay (i.e., the distance effect), that were nearly twice as large as those taking place while waiting motionless for nearly 10 s prior to movement initiation. This observation suggests very strongly that time per se is not the essence of the distance effect, but that it is movement duration that causes it. In addition, the results of the supplementary analysis reported in experiment 2 indicate that the distance effect does not appear to be linked to movement length per se but rather to movement duration, a position supported by the reversal of the distance effect observed for the experimental group in experiment 1. Taken together the above observations suggest that aiming to remembered target location interferes with its retention in memory, and that it is this interference that causes the distance effect.

Coding location of remembered target

When a target is extinguished prior to movement initiation, its location remains available in iconic memory for a short period of time (Lemay and Proteau 2001; Elliott and Calvert 1992; Elliott and Madalena 1987). Moreover, the results of partial report studies suggest that all the information available in the visual scene can be recalled (Sperling 1960). In that vein, Elliott and Calvert (1992) had participants perform a manual aiming task in a condition in which a single target could be used or while two targets could be presented at the same time. Participants performed the task in a normal vision condition, or in conditions in which all visual information was eliminated at the initiation of the aiming movement, at the presentation of a reaction signal, or 2 s prior to the reaction signal. These authors showed that the aiming error increased significantly from one of the above-defined conditions to the other, and was larger in the choice task than when a single target was used. However, the difference in aiming error found between the single and the choice conditions did not increase significantly as a function of the period of occlusion, which led the authors to propose that participants retained information 'about the layout of the movement environment' rather than about a single target location. Additional evidence that iconic memory intervened when pointing to recently extinguished targets is available in the present study.

In the first experiment of the present study, participants had a higher peak velocity for a 100-ms than for a 10,000-ms recall delay, whereas in the second experiment, peak velocity was higher when pointing to remembered targets than when pointing to visible targets. Similar observations have been reported by Lemay and Proteau (2001). They reported that the increase in peak velocity noted for shorter than for longer recall delays was totally eliminated in a masking condition – which is thought to 'erase' the content of iconic memory (see Elliott et al. 1990; Lowe 1975; Sperling 1960) – while that of variable error of aiming was larger in a mask than in a no-mask condition. Taken collectively, the results reported by Elliott and Calvert (1992), Lemay and Proteau (2001), and in both experiments of the present study, suggest that having a target representation in iconic memory favors aiming performance.

However, even when target location is available in a visual form such as in iconic memory, the results of the present study suggest that it is still required that the target location be recoded in an egocentric frame of reference for movement planning and control purposes (viewer-centered and/or arm-centered frame of reference; Carrozzo et al. 1999; McIntyre et al. 1998; Soechting and Flanders 1989a, b; Vindras and Viviani 1998). This is the case, because in experiment 1 the distance effect did not differ significantly between the short recall delay, when target location was presumably available in iconic memory, and the long recall delay when it clearly was not. Taken together, the above observations suggest that the iconic representation of the target can be used to update its egocentric representation.

In addition, finding a very similar distance effect after both a short and a long recall delay in experiment 1 suggests that target location was recoded in the same frame of reference, body- and/or arm-centered (Carrozzo et al. 1999; Chieffi et al. 1999; McIntyre et al. 1998; Vindras and Viviani 1998), in both recall conditions. This egocentric target representation, the resulting movement representation, or one's evaluation of his or her initial hand position (Vindras et al. 1998; Wann and Ibrahim 1992) would decay over time, which would explain at least partially the larger variable error and absolute constant error found in experiment 1 for the longer than for the shorter recall delay (see also Lemay and Proteau 2001 for a similar finding). The distance effect would result from interference between movement execution and maintaining this egocentric representation of the target location. Future work should address this possibility.

Finally, the results of the present study indicated that aging does not affect pointing to remembered targets. At least, this is the case when the task does not require that participants initiate and execute their movement as fast as possible. This conclusion is supported by recent evidence showing that the retaining of egocentric spatial information does not decrease with age (Desrocher and Smith 1998).

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