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# Gravitational pull does not explain undershooting target locations in complete darkness

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*WE DID IT!*

Abstract

A movement phenomenon exists in which upright individuals reaching to remembered target locations point lower when performing in the dark compared to normal room lighting. It has been suggested that producing less movement in darkness occurs because of gravitational influences particularly for targets farther away from starting hand position. The present study was used to explore the motor control of this “dark phenomenon.” Ten young healthy adults were asked to produce straight arm pointing movements to real and remembered target locations in UPRIGHT and INVERTED body orientations. Starting position of the dominant arm was extended DOWN by the hip or flexed UP by the ear. Three targets directly in front of the midline were presented at shoulder level and shoulder level ±30 cm. Prior to movement participants anchored their gaze on the displayed target before pointing to its real or remembered location. Targets in remembered trials were covered before pointing in normal room lighting (LIGHT) or complete darkness (DARK). At least 6 trials were performed to each target in each body orientation, starting arm position, and visual condition. Elevation errors of the shoulder-finger line were calculated for each participant and compared across target level, body orientation, and visual condition for each starting arm position using repeated measures ANOVAs. In the DARK participants often produced more negative errors when starting with the arm DOWN and more positive errors when starting with the arm UP, both corresponding to the undershooting of remembered target locations. Control of smaller movement amplitudes observed in darkness primarily with greater movement excursions occurred regardless of muscle activation or body orientation. The present study revealed that the effects of the

gravitational pull for endpoint precision in darkness are minimal at best, thus cannot explain the “dark phenomenon.”

## Introduction

Pointing and reaching towards objects are fundamental tasks commonly used in activities of daily living. Discrete movements made toward remembered target locations often result in different endpoint precision when compared to movements to actual targets seen by the observer. Interestingly, errors occur whether pointing to the remembered locations are performed in an environment with or without allocentric cues (vision of the environment) available. However, people do tend to point or reach below remembered target locations in darkness when compared to an illuminated environment, whether the movement happens while seated (Bock & Eckmiller, 1986; Bock, Howard, Money, & Arnold, 1992; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Henriques & Crawford, 2000) or standing with (Hondzinski & Cui, 2006) or without (Admiraal, Keijsers, & Gielen, 2004) taking a step. This leaves one to question the potential causes of the phenomenon of reaching or pointing lower in the dark.

One point to consider is that this “dark phenomenon,” pointing lower in darkness, occurs often in the vertical direction in alignment with the gravitational vector. Endpoint errors along the long body axis were most negative for the upright body orientation, thus more inferior than those for supine and prone body orientations in participants reaching with their eyes closed (Smetanin & Popov, 1997). These data provide evidence for gravitational influences, i.e. errors in endpoint accuracy are in the same direction as the gravitational pull. In contrast, greater movement excursions against the gravitational pull were used to achieve final endpoint locations in another study (Spindalieri & Sgolastra, 2001), suggesting evidence opposing the influence of the gravitational pull on endpoint accuracy. In this case greater errors in the inferior direction occurred in supine relative

to upright body orientations for blindfolded participants pointing to remembered target locations along the anterior surface of the trunk. Together these results provide contradictory evidence that gravitational acceleration affects accuracy when pointing to remembered target locations. The conflicting results and methods used in those studies do not allow for direct exploration of errors among the different body orientations along the gravitational axis to directly test potential gravitational influences.

Evidence for kinematic differences in pointing trajectories in an illuminated environment exist and have been linked to gravitational force influence on motor planning (Papaxanthis, Pozzo, Popov, & McIntyre, 1998). Trajectory asymmetries in acceleration between up and down arm movements do not occur when there is a continued equal gravitational influence on left and right horizontal pointing movements (Gentili, Cahouet, & Papaxanthis, 2007). These studies provide evidence that acceleration due to gravity is an important factor during vertical arm movement planning (Papaxanthis et al., 1998), which may directly influence endpoint precision.

Another point to consider for the “dark phenomenon” is that it occurs more often for targets positioned at a farther distance away from starting hand position. Participants who simultaneously reached and stepped to remembered target locations in the dark reached lower than those in normal room lighting for targets at shoulder height or higher (Hondzinski & Cui, 2006). For starting hand positions close to the hip, these targets required longer movement excursions than the target location approximating the mid-trunk height. Seated participants also under-reached remembered target locations that were furthest from the body and starting hand position when reaching anteriorly in darkness (Henriques, Medendorp, Gielen, & Crawford, 2003). Apparently the trend of

reaching with less displacement in darkness occurs most often for movement excursions of longer distances and do not always correspond to direction of the gravitational component.

There are two factors for the “dark phenomenon” observed in the literature that may or may not be linked—gravitational influence and hand displacement during task performance. The question remains: Does reaching and pointing below remembered target locations in the dark link to moving a shorter distance because of these factors or something else? Thus the purpose of the present work was to determine whether altering body orientation in relation to the gravitational vector would influence endpoint accuracy in pointing and do so regardless of environmental lighting. In order to directly measure this gravitational influence, participants in the present study were asked to point to remembered target locations requiring different movement excursions with and without allocentric cues available from upright and inverted body orientations. Since different muscles are used to raise and lower the arm when pointing to objects, starting arm position was also varied. This allowed for examination of the effects of various body orientations, the type of muscle contraction, and lighting conditions on endpoint accuracy. Based on outcomes of previous work it was hypothesized that endpoint errors would differ for the various body orientations in the direction of the gravitational pull for performances in complete darkness.

## Methods

*Subjects*:

One left-handed and nine right-handed participants between 18 and 33 years old (4 females, 6 males) gave written consent to participate in the experiment. All participants reported no neurological impairments and had visual acuity better than $20/30^{-1}$ (CM 4170 Snellen Eye Chart) with no difficulty viewing targets. Participants ranged in height from 155 cm to 180 cm. The Louisiana State University Institutional Review Board approved the following experimental procedures.

*Procedures:*

Feet of each participant were approximately shoulder width apart with the head and heels resting against a tilt table, while the body was positioned in standing UPRIGHT or INVERTED orientations. Participants started with the dominant arm extended down with the hand on the anterior surface of the leg (DOWN) or flexed up with the arm lateral to the ear (UP). Participants produced straight arm pointing movements to real (CONTROL) and remembered target locations in normal room lighting (LIGHT) and in complete darkness (DARK). Figure 1 shows the different body orientations and starting arm positions which allowed participants to move with and against the gravitational pull using the shoulder flexor and extensor muscles in an agonist and antagonist manner.

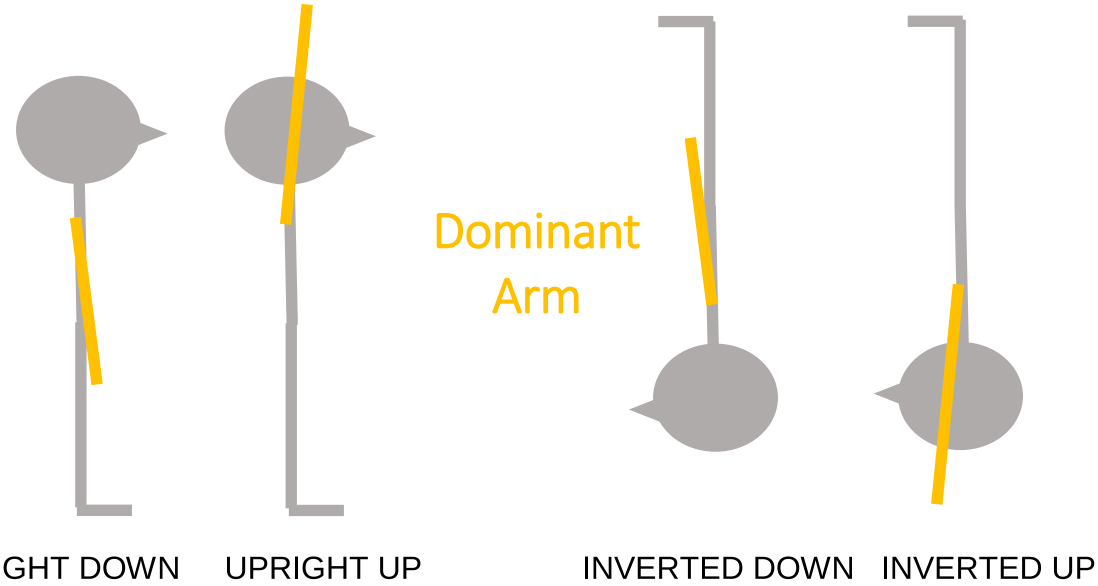


*Figure 1: Participants' starting positions.*

Three target levels including shoulder level (SHOULDER) and 30 cm superior (SUP) and inferior (INF) to the shoulder were located 152 cm directly in front of each participant's midline. Prior to movement, participants were instructed to anchor their gaze on the displayed target (1.5 cm in diameter) before pointing to its real or remembered location. They were instructed to make a single movement at a quick but comfortable pace when pointing. Targets were covered before the initiation of the pointing movement for remembered trials in LIGHT and DARK conditions. A trial progressed as follows. A participant anchored their gaze at a presented target. The presenter gave a "ready," pause for 1-2 seconds, then "go" signal. The "ready" cued an investigator to cover the target with a large black flap (about 50 cm X 30 cm) that blended with the black background in remembered target trials and turning off the lights in the DARK condition. Participants initiated movement on the "go" signal and held the final pointing position (Figure 2) until given a "relax" cue approximately 1 s after movement end to return to the starting position.

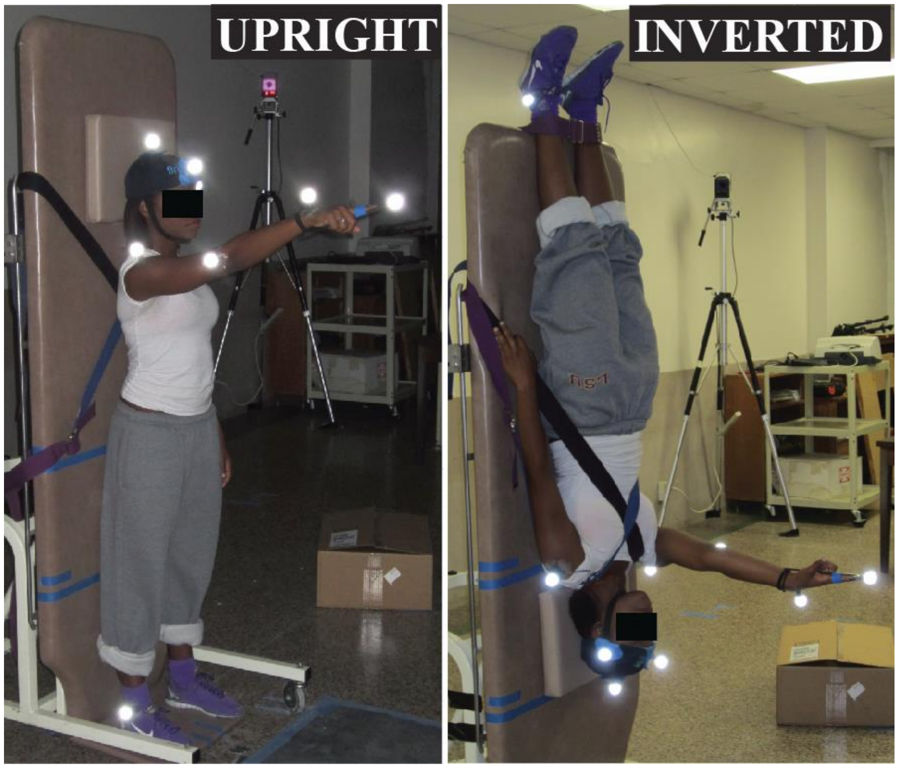


*Figure 2: A participant is shown in the UPRIGHT (left) and INVERTED (right) body orientations pointing to a remembered target location in the DARK and LIGHT conditions, respectively. Note the flash from the camera lit up the room in the DARK condition. These trials were only used to show experimental setup and not used in analyses.*

Six pointing trials were performed for each target level (SUP, SHOULDER, INF), body orientation (UPRIGHT, INVERTED), starting arm position (DOWN, UP), and visual condition (CONTROL, LIGHT, DARK). Table 1 shows the body orientation and starting arm position order for each participant. Trial order within a body orientation and starting arm position was pseudo randomized in blocks so that no more than 2 trials of each target level and visual condition were performed before moving to the next block.

Table 1: Participant's Body Orientation and Starting Arm Position Order

| Subject Number | First Starting Position | Second Starting Position | Third Starting Position | Fourth Starting Position |
|---|---|---|---|---|
| 1 | UPRIGHT DOWN | INVERTED DOWN | UPRIGHT UP | INVERTED UP |
| 2 | UPRIGHT DOWN | INVERTED DOWN | INVERTED UP | UPRIGHT UP |
| 3 | UPRIGHT DOWN | INVERTED DOWN | UPRIGHT UP | INVERTED UP |
| 4 | INVERTED DOWN | UPRIGHT DOWN | UPRIGHT UP | INVERTED UP |
| 5 | UPRIGHT DOWN | INVERTED DOWN | INVERTED UP | UPRIGHT UP |
| 6 | INVERTED DOWN | INVERTED UP | UPRIGHT DOWN | UPRIGHT UP |
| 7 | INVERTED DOWN | INVERTED UP | UPRIGHT DOWN | UPRIGHT UP |
| 8 | UPRIGHT DOWN | UPRIGHT UP | INVERTED DOWN | INVERTED UP |
| 9 | INVERTED DOWN | INVERTED UP | UPRIGHT DOWN | UPRIGHT UP |
| 10 | INVERTED DOWN | INVERTED UP | UPRIGHT DOWN | UPRIGHT UP |

*Data Collection:*

Ten reflective markers with diameters of 2.5 cm were placed on the participant in the follow positions: forehead, top of head, and non-dominant side of head on adjustable hat, non-dominant shoulder and ankle, dominant shoulder, elbow, wrist, and pointer finger, and ankle (Figure 2). The data were collected using the Qualisys passive marker motion system (Qualisys Medial AB, SE) in 2 minute intervals at 60 Hz. Trials were repeated when participants did not follow directions (i.e. made obvious double pointing movements, moved before the "go" signal, etc). Extra trials were randomly presented and performed in cases when all scheduled trials were completed and time was left in the 2 minute data collection interval.

*Data Analyses:*

Position data were passed through a 6 Hz low-pass second order Butterworth filter with forward and reverse pass to filter data with zero phase shifts. Tangential velocity of the fingertip was calculated by differentiating position data with respect to time. The shoulder-fingertip line represented the imaginary line segment from the

markers on the dominant shoulder and the fingertip. Elevation errors of the shoulder-fingertip line at movement end (determined when fingertip velocity reached 5% of its peak during movement deceleration) during LIGHT or DARK conditions were determined relative to the mean of control trials (i.e. LIGHT or DARK trial elevation error – mean control elevation error) in an egocentric frame of reference (see Figure 3). Positive errors represent pointing more superior than a control mean. Thus overshooting remembered target locations corresponds to positive errors in the arm DOWN position and negative errors in the arm UP position. The peak (maximum) velocity (VEL) of the movement was determined and a threshold of 5% of the peak was used to define start and end points of the movement. Movement time (MT) was calculated as the difference in time between start and end movement points.

Mean errors, displacement, MT, and VEL and their standard deviations (SD) were calculated separately for SUP and INF targets, LIGHT and DARK visual conditions, UPRIGHT and INVERTED body orientations for each subject in each starting arm position. We included only SUP and INF targets to ensure similar shoulder gravitational torques in final pointing positions similar to previous work (Papaxanthis et al., 2005) as well as to emphasize the possible differences in endpoints for different lengths of movement excursions. Effects of target level (TARG), body orientation (ORIENT), and visual condition (VIS) and their interactions for each starting arm position were analyzed using repeated measures ANOVAs ($\alpha$=0.05). Data were also reduced to include only single pointing movements for analysis to reduce the variability in the results. Analyses were performed on complete and reduced data sets to

determine if performances including corrections differed from those only on single pointing movements.

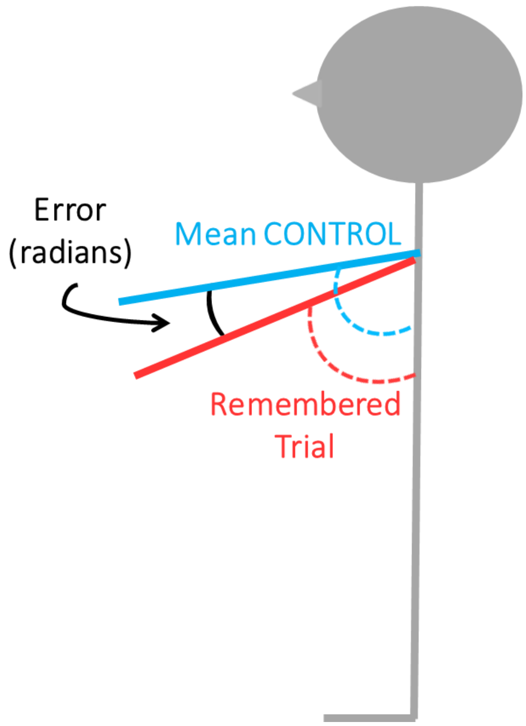


*Figure 3: Each elevation error (radians) represents the difference between elevation angles of the shoulder-fingertip line for each remembered trial (red) and the corresponding mean of CONTROL trials (blue).*

## Results

### Arm DOWN

#### *Elevation Errors*

Figure 4 represents examples of final pointing position of the shoulder-fingertip line for one participant who began with their arm in the DOWN position. Final pointing positions for the three visual conditions are provided for the SUP target for both body

orientations. Note that in the DARK condition participants commonly pointed more inferior relative to the final locations of CONTROL and LIGHT conditions.

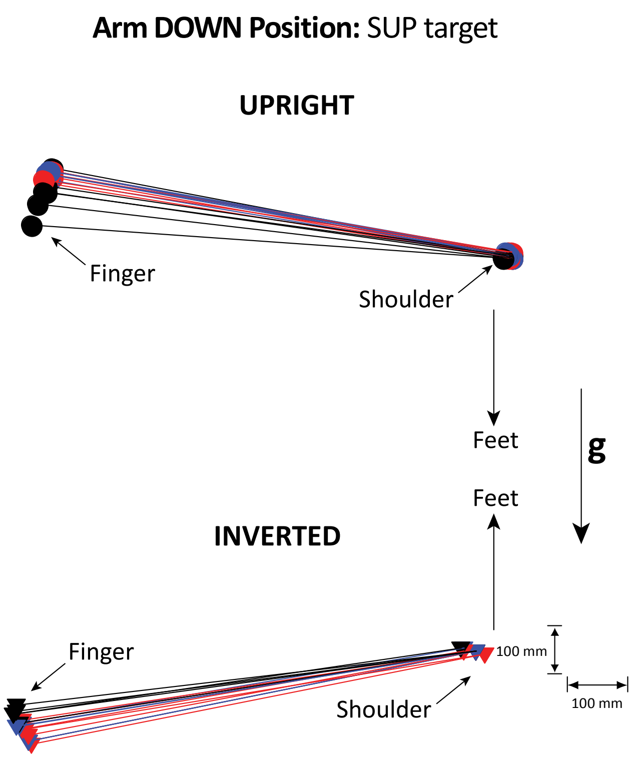


*Figure 4: Final shoulder and fingertip locations for the UPRIGHT (circles) and INVERTED (triangles) body orientations for the arm DOWN starting position to the SUP target for participant 1. The shoulder-fingertip lines which connect these markers are color coded by visual conditions: blue for CONTROL, red for LIGHT, and black for DARK.*

Table 2 depicts the results for constant and variable elevation errors before (complete) and after reducing (reduced) the number of trials based on single movements for the arm DOWN position (reduced > 77% of complete trials). Results for the complete trials are presented first. The main effects of VIS and TARG revealed that constant elevation errors in the DARK condition and for SUP targets were more negative than errors in the LIGHT and for INF targets, respectively. The significant TARG x VIS interaction shown in Figure 5 revealed that in the LIGHT condition

participants' final pointing locations were most accurate (i.e. mean values close to zero). In the DARK participants had more negative errors than in the LIGHT but this difference was only significant for the SUP target. These negative errors correspond to undershooting remembered target location. Most participants demonstrated a similar trend for the INF target (*P*=0.08); that they often produced more negative errors than in the LIGHT condition. Lastly, elevation errors were most variable in the DARK visual condition and INVERTED body orientation.

*Table 2: Arm DOWN Elevation Error Results*

| **Error Type** | **Complete** | | **Reduced** | |
|---|---|---|---|---|
| ***CONSTANT*** | $F_{(1,9)}$ -value | *P-value* | $F_{(1,8)}$ value | *P-value* |
| TARG | 14.73 | 0.004 | 6.78 | 0.031 |
| VIS | 14.00 | 0.005 | 15.44 | 0.004 |
| TARG x VIS | 13.06 | 0.006 | 7.40 | 0.026 |
| ***VARIABILITY*** | $F_{(1,9)}$ -value | *P-value* | $F_{(1,8)}$ value | *P-value* |
| ORIENT | 17.92 | 0.002 | 8.47 | 0.027 |
| VIS | 58.76 | 0.000 | 43.69 | 0.001 |

Table 2 also reveals that similar outcomes existed for the complete and reduced data sets. Whether considering single pointing trials (reduced) or not, participants had the most negative elevation errors in the DARK for the SUP target and the greatest variability for the INVERTED body orientation and in the DARK visual condition (data not shown).

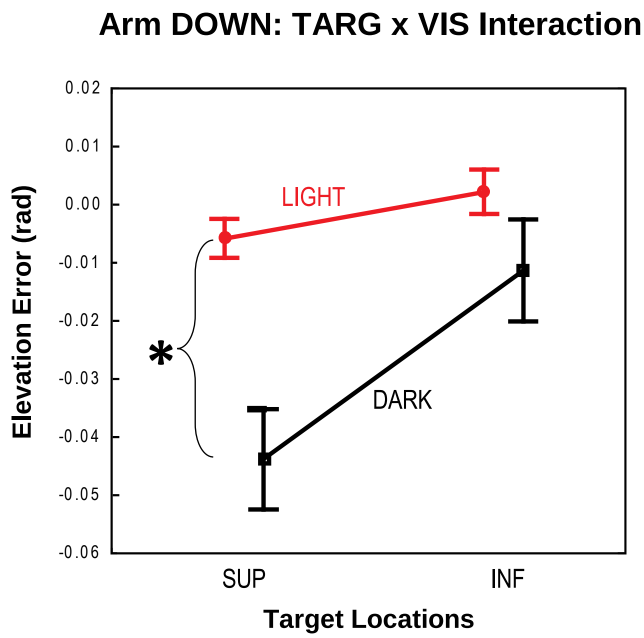


*Figure 5: The TARG x VIS interaction for elevation errors in the arm DOWN starting position. Red represents the LIGHT condition and black the DARK condition for SUP (left) and INF (right) target levels. Error bars represent ±1 standard error. Asterisk represents a significant difference between visual conditions for the given target level (P<0.05).*

*Displacement*

Table 3 shows the significant outcomes for displacement in the arm DOWN position. These results revealed a main effect of TARG on displacement showing greater displacement for the SUP target relative to the INF target. These results logically define that the SUP target was the farthest away from the hand in the arm DOWN starting position. The main effect of VIS on displacement showed that participants had the longest movement excursions in the LIGHT condition. The significant TARG x VIS interaction showed that participants had greater displacement while pointing to the SUP target in the LIGHT condition compared to the DARK condition (Figure 6), demonstrating that participants undershot the target location in the DARK. The significant ORIENT x TARG interaction showed that the greatest

displacement was to the SUP target while INVERTED, but that displacement differed more for the INF target despite body orientation (Figure 7). Results revealed no significant effects on displacement variability for this starting arm position. The results from the reduced data set paralleled the main effects for mean displacement and the TARG x VIS interaction, yet the ORIENT x TARG interaction was not significant.

*Table 3: Arm DOWN Displacement Results*

| | **Complete** | | **Reduced** | |
|---|---|---|---|---|
| ***MEAN*** | $F_{(1,9)}$ *value* | *P-value* | $F_{(1,8)}$ *value* | *P-value* |
| TARG | 1105.01 | 0.000 | 643.81 | 0.000 |
| VIS | 17.89 | 0.002 | 13.29 | 0.007 |
| ORIENT x TARG | 7.43 | 0.023 | | |
| TARG x VIS | 11.92 | 0.007 | 13.05 | 0.007 |

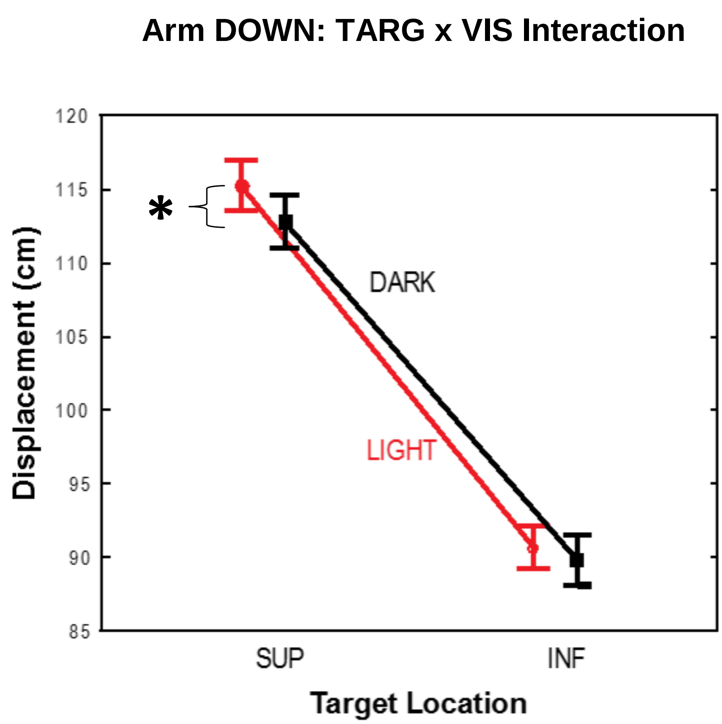


*Figure 6: The TARG x VIS interaction for displacement in the arm DOWN starting position. Red represents the LIGHT condition and black the DARK condition for SUP (left) and INF (right) target levels. Error bars represent ±1 standard error. Asterisk represents a significant difference between visual conditions for the given target level (P<0.05).*

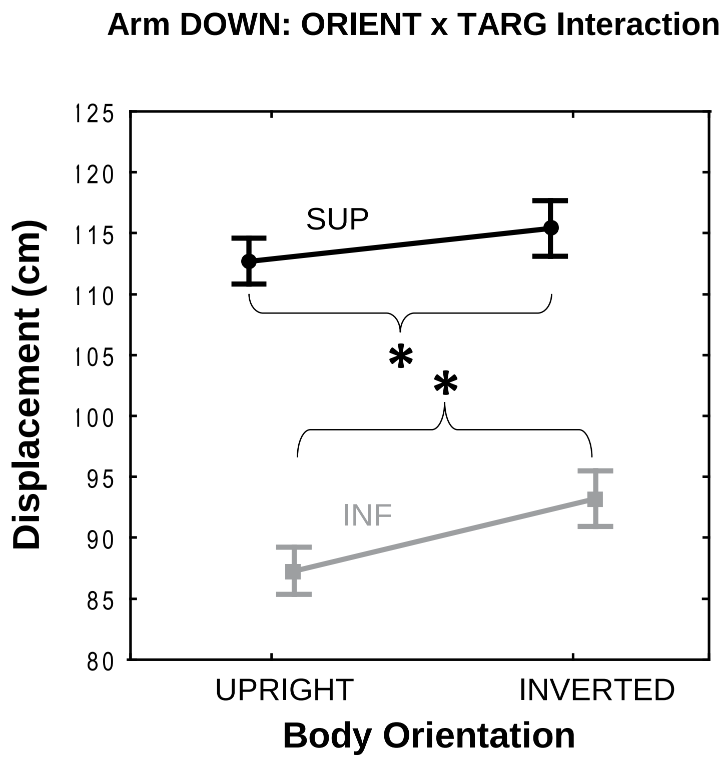


*Figure 7: The ORIENT x TARG interaction for displacement in the arm DOWN starting position. Gray represents the INF target level and black the SUP target level for UPRIGHT (left) and INVERTED (right) body orientations. Error bars represent ±1 standard error. Asterisk represents a significant difference between body orientations for the given target level (P<0.05).*

*Peak Velocity and Movement Time*

Main effects of TARG ($F_{(1,9)}$ =167.29, P<0.0001) and VIS ($F_{(1,9)}$ =63.86, P<0.0001) on  peak velocity revealed that participants moved at greater peak velocities while moving towards the SUP target and in the LIGHT condition than to the INF target and in the DARK condition, respectively. Figure 8 shows that despite body orientation, participants continued to have greater peak velocities in the LIGHT condition, however this difference was greater for the INVERTED body orientation (ORIENT x VIS interaction: $F_{(1,9)}$ =11.60, P<0.01). Participants showed greatest variability in peak

velocity in the LIGHT visual condition (VIS: $F_{(1,9)}$ =41.36, P<0.001) and when pointing to the SUP target (TARG: $F_{(1,9)}$=121.53, P<0.0001).

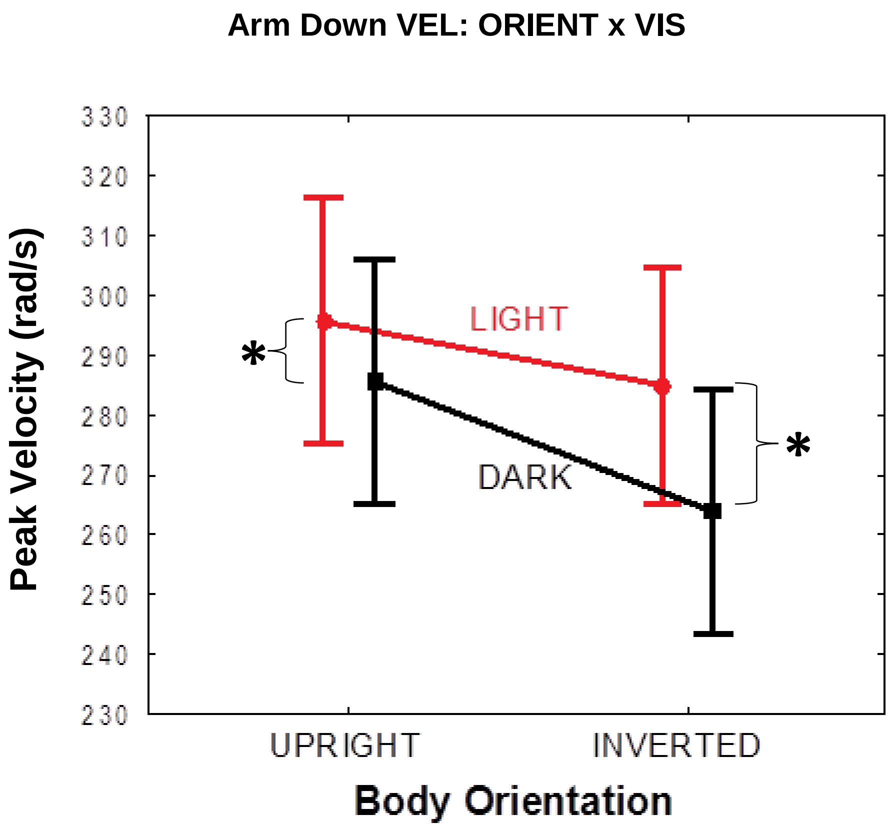


*Figure 8: The ORIENT x VIS interaction for peak velocity in the arm DOWN starting position. Red represents the LIGHT visual condition and black the DARK visual condition for UPRIGHT (left) and INVERTED (right) body orientations. Error bars represent ±1 standard error. Asterisk represents a significant difference between visual conditions for the given body orientation (P<0.05).*

Participants revealed the longest movement times while INVERTED and in the DARK condition (main effects of ORIENT ($F_{(1,9)}$ =8.73, P<0.05) and VIS ($F_{(1,9)}$ =11.96, P<0.01) on MT). For the INF target, participants also produced the longest movement time in the DARK condition (TARG x VIS interaction: $F_{(1,9)}$ = 9.01, P<0.05, Figure 9).

Participants' movement times were also most variable while INVERTED (ORIENT: $F_{(1,9)}$ =31.39, P<0.001).

**Arm DOWN MT: TARG x VIS**

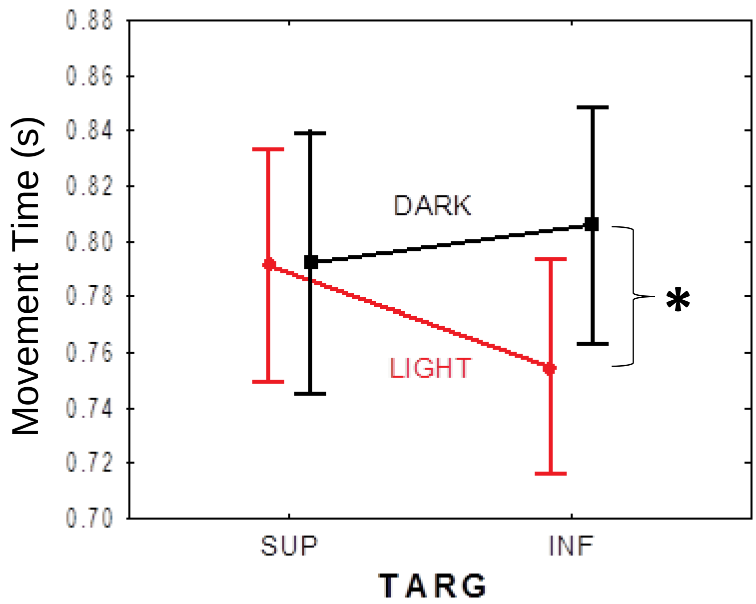


*Figure 9: The TARG x VIS interaction for movement time in the arm DOWN starting position. Red represents the LIGHT visual condition and black the DARK visual condition for SUP (left) and INF (right) target levels. Error bars represent ±1 standard error. Asterisk represents a significant difference between visual conditions for the given target level (P<0.05).*

Again, reduced results paralleled complete results for peak velocity but differed slightly for those of movement time. Participants produced the greatest peak velocities when pointing in the LIGHT condition (VIS: $F_{(1,8)}$=33.84, P<0.001) and to the SUP target (TARG: $F_{(1,8)}$=196.43, P<0.0001). This corresponds with the notion that participants had the greatest movement times in the DARK condition (VIS: $F_{(1,8)}$=6.87, P<0.05). The significant OREINT x TARG interaction ($F_{(1,8)}$=8.51, P<0.05) revealed that participants took longer to move in the INVERTED body orientation relative to the UPRIGHT and

this difference was greater for the INF target location. The analysis on the reduced data did not reveal significant variability for peak velocities and movement time.

Arm UP

*Elevation Errors*

Figure 10 represents examples of final pointing position of the shoulder-fingertip line for trials originating in the arm UP position for the same participant presented in Figure 4. Note that in the DARK condition participants commonly point more superior (i.e. once again undershooting remembered target locations) relative to the final locations of control and LIGHT conditions, especially when inverted.

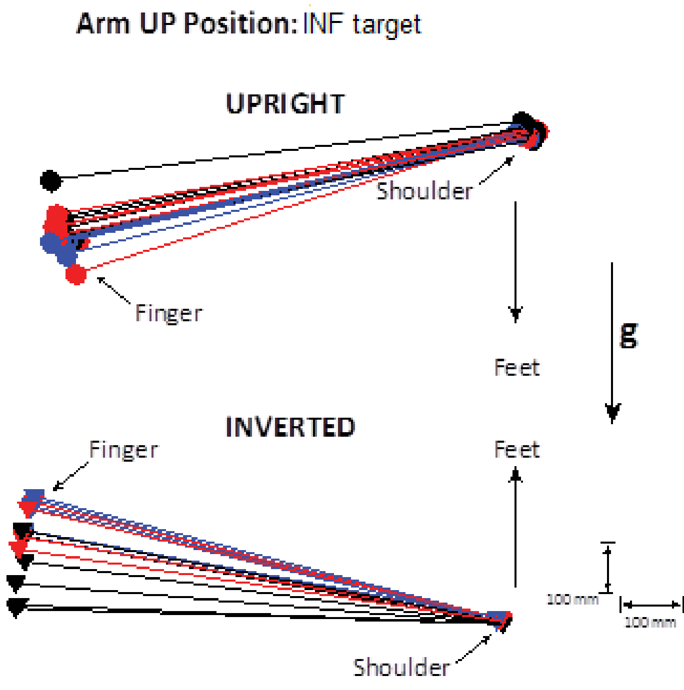


*Figure 10: Final shoulder and fingertip locations for the UPRIGHT (circles) and INVERTED (triangles) body orientations for the arm UP starting position when pointing to INF target for participant 1. The shoulder and fingertip markers and the lines which connect these markers are color coded by visual conditions: blue for CONTROL, red for LIGHT, and black for DARK.*

Table 4 depicts the results of the analyses for constant and variable elevation errors before (complete) and after reducing (reduced) the number of trials based on single movements for the arm UP starting position (reduced > 81% of complete trials). While INVERTED, participants demonstrated greater elevation errors than while UPRIGHT (main effect of ORIENT) as well as greater errors when pointing to the INF target compared to the SUP target (main effect of TARG). Specifically, participants had the greatest positive error when pointing to the INF target while INVERTED (significant ORIENT x TARG interaction) or performing the task in the DARK condition (main effect of VIS), however, the significant ORIENT x TARG x VIS interaction revealed that errors between LIGHT and DARK conditions were not significant when pointing to the SUP target while INVERTED (P=.05, Figure 11). Participants had the greatest variability while INVERTED (main effect ORIENT), in the DARK condition (main effect VIS), and when pointing to the INF target (main effect TARG).

*Table 4: Arm UP Elevation Error Results*

| **Error Type** | **Complete** | | **Reduced** | |
|---|---|---|---|---|
| ***CONSTANT*** | $F_{(1,9)}$ *value* | *P-value* | $F_{(1,9)}$ *value* | *P-value* |
| ORIENT | 19.90 | 0.002 | 15.44 | 0.003 |
| TARG | 10.55 | 0.010 | 8.74 | 0.016 |
| VIS | 10.65 | 0.010 | 10.40 | 0.010 |
| ORIENT x TARG | 12.86 | 0.006 | 12.53 | 0.006 |
| ORIENT x TARG x VIS | 31.54 | 0.000 | 14.02 | 0.005 |
| ***VARIABLE*** | $F_{(1,9)}$ *value* | *P-value* | $F_{(1,9)}$ *value* | *P-value* |
| ORIENT | 6.96 | 0.027 | | |
| TARG | 10.94 | 0.009 | | |
| VIS | 41.75 | 0.000 | 24.42 | 0.001 |

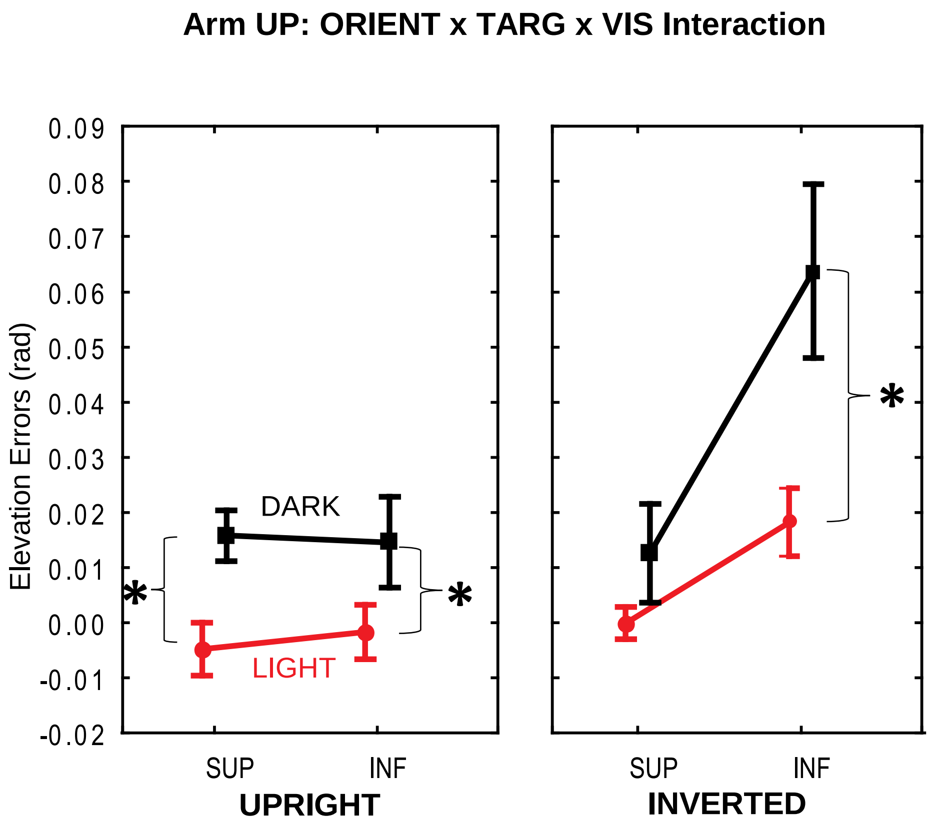


*Figure 11: The ORIENT x TARG x VIS interaction for elevation errors in the arm UP starting position. Red represents the LIGHT condition and black the DARK condition for SUP (left) and INF (right) target levels within each box. The left box represents errors for the UPRIGHT body orientation, while the right box represents errors for the INVERTED body orientation. Error bars represent ±1 standard error. Asterisks represent significant differences between visual conditions for the given target level and body orientation (P<0.05).*

Table 4 also reveals similar outcomes for the complete and reduced data sets for constant elevation errors when participants started in the arm UP position. Although participants continued to demonstrate more variability in the DARK condition (main effect VIS), the main effects of ORIENT and TARG were no longer significant for these variable errors.

*Displacement*

Table 5 shows that participants demonstrated the greatest displacement while UPRIGHT (main effect ORIENT), in the LIGHT condition (main effect of VIS), and when pointing to the INF target location (main effect of TARG). The significant 3-way interaction portrayed that participants moved less (i.e. undershot remembered target locations) in the DARK condition when pointing to the SUP target while UPRIGHT and when pointing to the INF target while INVERTED (Figure 12). Participants were most variable in displacement when pointing in the DARK condition (main effect VIS).

*Table 5: Arm UP Displacement Results*

| | **Complete** | | **Reduced** | |
|---|---|---|---|---|
| ***MEAN*** | *F(1,9) value* | *P-value* | *F(1,9) value* | *P-value* |
| ORIENT | 204.08 | 0.000 | 159.70 | 0.000 |
| TARG | 709.91 | 0.000 | 726.64 | 0.000 |
| VIS | 22.84 | 0.001 | 18.68 | 0.002 |
| ORIENT x TARG x VIS | 12.11 | 0.007 | 8.60 | 0.017 |
| ***VARIABLE*** | *F(1,9) value* | *P-value* | *F(1,9) value* | *P-value* |
| VIS | 9.25 | 0.014 | | |

Reduced results for displacement paralleled those previously stated with the exception that the 3-way interaction showed no difference between LIGHT and DARK conditions when pointing to the SUP target while UPRIGHT (data looked very similar to those in Figure 12 with no visual condition differences while UPRIGHT; in the left box). Participants did not show any significant variability in reduced trials.

**Arm UP: ORIENT x TARG x VIS Interaction**

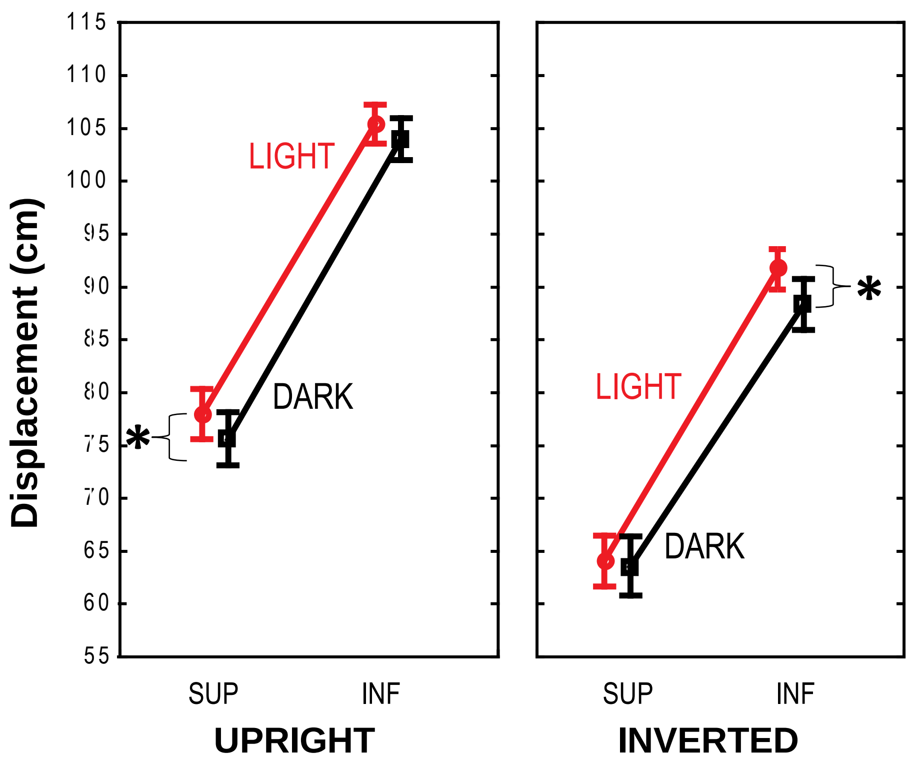


*Figure 12: The ORIENT x TARG x VIS interaction for displacement in the arm UP starting position. Red represents the LIGHT condition and black the DARK condition for SUP (left) and INF (right) target levels within each box. The left box represents endpoint errors for the UPRIGHT body orientation, while the right box represents endpoint errors for the INVERTED body orientation. Error bars represent ±1 standard error. Asterisks represent significant differences between visual conditions for the given target level and body orientation (P<0.05).*

*Peak Velocity and Movement Time*

In the arm UP starting position the effects of TARG on VEL ($F_{(1,9)}$=194.59, P<0.0001) and MT ($F_{(1,9}$=24.24, P<0.001) revealed that participants produced a smaller peak velocity and took less time to move to the SUP target compared to the INF target. A significant ORIENT x TARG x VIS interaction for MT ($F_{(1,9}$=10.39, P<0.05)

demonstrated that participants produced the longest movement times while UPRIGHT and pointing to the INF target in the DARK condition (Figure 13). This interaction also revealed that pointing in the DARK took longer than pointing in the LIGHT for the INVERTED condition when pointing to the SUP target. A main effect of VIS on peak velocity ($F_{(1,9)}$=10.02, P<0.05) indicated that participants had greater peak velocities for the LIGHT condition compared to the DARK condition.

**Arm UP MT: ORIENT x TARG x VIS**

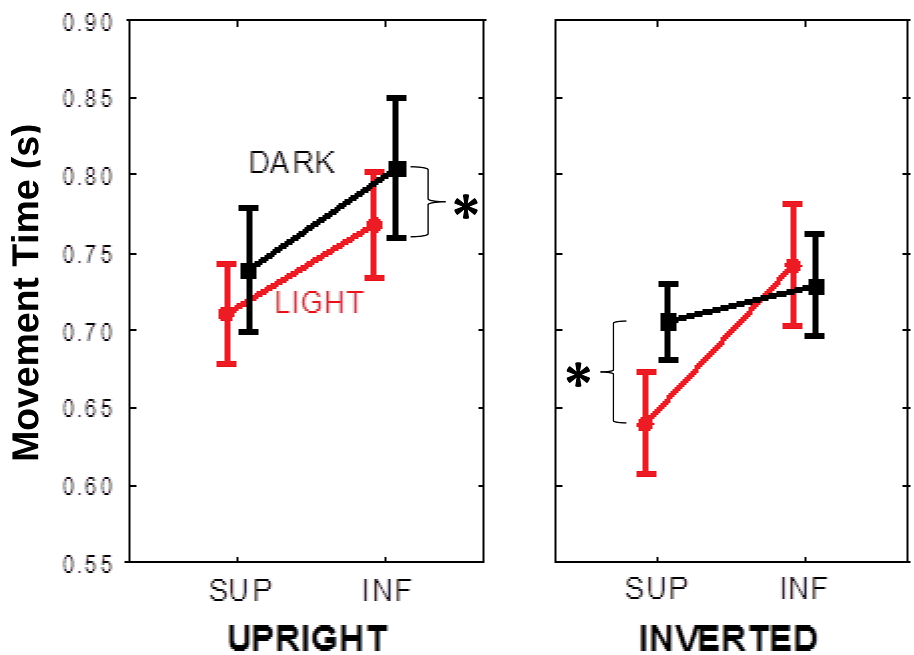


*Figure 13: The ORIENT x TARG x VIS interaction for movement time in the arm UP starting position. Red represents the LIGHT condition and black the DARK condition for SUP (left) and INF (right) target levels within each box. The left box represents errors for the UPRIGHT body orientation, while the right box represents errors for the INVERTED body orientation. Error bars represent ±1 standard error. Asterisks represent significant differences between visual conditions for the given target level and body orientation (P<0.05).*

Peak velocity outcomes for complete and reduced trials were very similar. However, the analyses on reduced trials revealed additional significant main effect of ORIENT ($F_{(1,9)}$=8.25, P<0.05) and TARG x VIS interaction ($F_{(1,9}$= 13.53, P<0.01) on MT such that participants produced longer movement times while UPRIGHT than INVERTED and when pointing in the DARK compared to the LIGHT to the SUP target.

## Discussion

Results of the current study revealed that whether in UPRIGHT or INVERTED body orientations participants commonly undershot remembered target locations in the DARK condition relative to the LIGHT condition. These outcomes correspond to previous literature in which participants frequently reached or pointed below remembered target locations when moving in complete darkness from seated (Bock & Eckmiller, 1986; Bock et al., 1992; Henriques et al., 1998; Henriques & Crawford, 2000) or standing (Admiraal et al., 2004) body orientations as well as when reaching with a step (Hondzinski & Cui, 2006). In these studies, achieving endpoints in complete darkness below those of corresponding conditions with lights on revealed that participants tend to undershoot remembered target locations in darkness, which also happened to be in the direction of the gravitational pull. However, the present results show that the major gravitational influences on endpoint accuracy regardless of body orientation (Smetanin & Popov, 1997) *do not explain* the undershooting that commonly occurs in darkness relative to conditions with allocentric cues available. These findings improve our understanding of the “dark phenomenon” and change its definition from “pointing lower in darkness” to “pointing less distance in darkness.”

Results of the current study also revealed that straight arm undershooting of remembered target locations in the DARK occurred most often for longer movement excursions. The largest deviations from zero (negative errors) for the DARK condition occurred when participants began with the arm DOWN and pointed to the SUP target location (see Figures 4 and 5) or began with the arm UP in the INVERTED body orientation and pointed to the INF target location (see Figure 10 and right panel of Figure 11). Participants also revealed less displacement of the fingertip in these instances (see Figures 6 and 12), demonstrating that participants move less in the DARK which may explain the greater errors that occur. These results contribute to the evidence that movement excursions decrease for larger movement amplitudes with no vision of the arm (Bock & Eckmiller, 1986) or in complete darkness (Hondzinski & Cui, 2006); (Henriques et al., 2003). Participants in the current study also showed some evidence of undershooting remembered target locations for relatively short pointing movements. Remember that errors for the DARK condition were greater than those in the LIGHT condition for UPRIGHT participants starting with the arm UP regardless of target location (see left panel, Figure 11). Accordingly, these outcomes corresponded to the smaller fingertip displacement that occurred for the DARK relative to LIGHT condition in this situation (see left panel, Figure 12), suggesting once again shorter movement excursions in darkness. Furthermore, since overreaching of more proximal target locations in illuminated settings is consistent in literature(Soechting & Flanders, 1989; Gentilucci & Negrotti, 1994; Tresilian, Mon-Williams, & Kelly, 1999; Henriques et al., 2003), it should not be surprising that by under reaching in the dark participants can have better precision in some cases (e.g. (Hondzinski & Cui, 2006)).

Although different planning processes are likely used for up and down pointing movement trajectories (Papaxanthis, Pozzo, & Schieppati, 2003), the present results provide evidence that similar planning processes are likely used for vertical endpoint precision despite movement direction or body orientation. In order to perform the task, participants needed to generate force in the upper extremity through concentric and eccentric muscle contractions. While UPRIGHT with the starting arm position DOWN, the participants will concentrically contracting the flexor muscles such as the anterior deltoid to lift the arm to point to the target location (Papaxanthis et al., 2003). These authors showed that when moving slowly, the same flexor muscles used to lift the arm were the only muscles utilized to slow the arm against the gravitational pull toward movement end. This outcome opposes the existence for non-reciprocal inhibition for this movement. Moreover, when starting with the arm up, participants contract the anterior deltoid eccentrically to lower the arm against the gravitational pull, like those UPRIGHT participants starting with the arm UP in the current study. One can reason that the opposite holds true when inverted. When the starting arm position is UP, participants would concentrically activate the extensor muscles of the arm such as the latissimus dorsi to move the arm against the gravitational pull. Similar to the UPRIGHT body orientation, these muscles would slow the arm toward the end of movement and would be eccentrically activated when pointing from the arm starting position DOWN. Interestingly, there was a co-contraction of flexor and extensor muscles during fast movements regardless of up or down pointing movements (Papaxanthis et al., 2003). Despite the differences in muscle activation patterns, participants in the present study continued to have similar vertical endpoint errors within each visual condition,

suggesting similar planning goals for endpoint precision during up and down pointing movements.

In the DARK condition, participants produced slower movements and achieved smaller peak velocities for shorter movement excursions than in the LIGHT condition, frequently leading to more errors. Clearly the speed-accuracy trade-off observed often for discrete movements (e.g. (Wu, Kwon, & Kowler, 2010)) does not hold true across visual conditions when movement speeds are comfortably paced and self-selected. In order to gain greater insight to the potential influences on endpoint precision, Pearson correlations were performed to determine within subject associations of endpoint errors with peak velocity, movement time, and displacement on single movement trials (i.e., reduced trials). Analyses revealed significant associations only between endpoint errors and displacements within most subjects. Table 6 shows significant positive associations for 7/10 and 8/10 subjects for SUP and INF target locations, respectively when participants began with the arm position DOWN and significant negative associations for 8/10 subjects for the INF target location when participants began with the arm position UP. These data support the previous findings that endpoint errors were associated with movement excursions. Moreover, they suggest no links of endpoint errors with movement time or peak velocity to account for differences in endpoint precision. These findings support those of previous research that indicated no significant correlations between endpoint errors and movement time of young adults when stepping and reaching toward remembered target locations in normal room lighting at a self-selected comfortable pace (Hondzinski, Li, & Welsch, 2010).

Table 6: Number of Significant Within Subject Correlations

| | **Displacement** | | **Peak Velocity** | | **Movement Time** | |
|---|---|---|---|---|---|---|
| | SUP | INF | SUP | INF | SUP | INF |
| **Elevation Error (DOWN)** | +7 | +8 | +2 | +2, -1 | 0 | +2, -1 |
| **Elevation Error (UP)** | -1 | -8 | 0 | -5 | 0 | -1 |

+ positive correlation; - negative correlation

This study revealed clearly that the acceleration due to the gravitational pull does not explain the undershooting of remembered target locations in darkness relative to an illuminated environment. Although additional research is needed to explain the "dark phenomenon" in full, the following reasoning offers a potential starting point for future studies in this area.

Moving less distance could be an implication of a natural body defense to protect oneself from too much movement when allocentric cues are not available. One could clearly note that the CNS needs to decrease movement amplitude to reduce joint stress at the extreme range of movement to avoid injury (e.g. (Reid, 1988)) or to stop the movement short in order to prevent collision with an object. Although participants in the present study were subjected to neither situations just mentioned, the control mechanisms may still be valid in darkness. Participants rely on visual and proprioceptive cues for final pointing position in the LIGHT condition, however, in the DARK condition only proprioceptive cues are available to participants. Although slower movements can use the same muscle to lift and lower the arm, faster movements make use of agonist and antagonist muscles (Papaxanthis et al., 2003). The lack of associations for endpoint errors with movement time and peak velocity observed in this study suggest that possible explanations for the "dark phenomenon" for faster movements include changes in the relative timing of antagonist and agonist muscle

activation when pointing in darkness. Understanding the control of this phenomenon would likely give insight to whether it is truly linked to protective mechanisms or not.

## Conclusion

Regardless of gravitational influence, participants had a tendency to undershoot the remembered target location in the DARK compared to the LIGHT. Outcomes revealed that the greater errors observed in the DARK condition primarily resulted from less vertical displacement, especially for longer excursions required to reach final target location rather than the influence of the gravitational pull. Although different planning processes are likely used for up and down pointing movement trajectories (Papaxanthis et al., 2003), the present results suggest similar planning process are likely used for vertical endpoint precision despite body orientation or starting arm position.

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