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Time of day shapes explicit and implicit contributions to visuomotor adaptation

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ABSTRACT

Motor adaptation relies on the interaction between explicit and implicit processes. Although these processes have been extensively characterized in visuomotor adaptation, how they vary across the day—and whether they show similar sensitivity to time of day—remains unknown. Here, we examined the influence of time of day on visuomotor adaptation and dissociated the contributions of explicit and implicit processes across three experiments. Participants completed adaptation tasks either in the morning or in the afternoon, under conditions that engaged both processes together or isolated each process. Participants tested in the afternoon adapted more rapidly during the early phase of visuomotor adaptation. This advantage was associated with more stable and directionally appropriate explicit strategy, whereas implicit adaptation remained unchanged throughout the day. When explicit and implicit processes were isolated, no time-of-day differences emerged. During the late phase of adaptation, performance was comparable across groups in all experiments. These findings show that daily fluctuations in motor adaptation arise primarily from changes in the interaction between explicit and implicit processes, providing new insight into how internal brain states shape adaptive behaviour and highlighting the potential importance of training time for motor rehabilitation.

INTRODUCTION

From the moment we rise in the morning, the successful accomplishment of our tasks depends on our ability to continuously adapt our movements to changing internal states and external demands. For instance, when walking on slippery pavement while running late, we may deliberately increase our walking speed to reach our destination on time, while automatically adjusting our gait to maintain balance and prevent slipping. This adaptive behaviour relies on the interaction between explicit and implicit processes, through which the motor system produces accurate and efficient movements based on available sensory information, cognitive resources, and its current internal state. The explicit process of adaptation involves voluntary, strategic adjustments aimed at rapidly optimising motor performance (e.g., increases in walking speed), while the implicit process involves the automatic updating of internal models that underlie movement execution (e.g., gait adjustments).

At the neurophysiological level, researchers commonly associate explicit process with the recruitment of prefrontal regions—particularly the dorsolateral prefrontal cortex—which support cognitive control and strategic adjustments¹, whereas implicit process has largely been linked to

cerebellar-dependent mechanisms that underpin the updating of internal models². At the computational level, early state-space models framed motor adaptation as a unitary process driven by trial-by-trial error correction^{3,4}. Smith et al. (2006) later extended these models with a two-state framework that distinguished fast and slow learning processes, often associated with explicit and implicit adaptation, respectively⁵. More recent computational approaches, including Bayesian models of error integration and disturbance observer frameworks, further emphasise the complexity of these interactions, suggesting that multiple processes may operate simultaneously and influence one another in non-trivial ways^{6,7}.

Whether the explicit and implicit processes operate independently^{8–12} or interact, compete, and influence one another during adaptation^{13–15} remains highly debated. Beyond the question of interaction, a closely related issue concerns the relative contribution of these processes to adapted behaviour, which may vary with task demands and internal state. Indeed, task-related characteristics, such as the nature and availability of sensory feedback, can strongly shape the explicit/implicit balance: endpoint feedback facilitates the use of explicit strategies, whereas continuous visual feedback tends to promote implicit adaptation^{10,16}. Similarly, alterations to the sensory environment, such as those induced by virtual reality, have been shown to increase reliance on explicit strategies and reduce implicit adaptation compared with conventional settings¹⁷.

On the other hand, internal factors, such as cognitive load, mental fatigue, and age, have also been shown to influence the relative contributions of explicit and implicit processes to adaptation. Increased cognitive demands or mental fatigue constrain strategic adjustments, leading to greater reliance on implicit adaptation^{18,19}. A comparable pattern is observed across the lifespan, with ageing reducing explicit capacities while implicit adaptation remains relatively preserved, resulting in a reorganisation of the relative contributions of these processes²⁰. These observations reinforce the idea that the motor system maintains performance by relying on the most efficient processes available under a given set of conditions.

One important parameter that could influence adaptive processes is the brain's functional state. Rather than being static, sensorimotor and cognitive functions fluctuate throughout the day and night, in response to circadian rhythms and ongoing physiological processes, including physical and cognitive activities. Although several studies have demonstrated the beneficial effects of sleep on consolidation processes^{21–23}, little attention has been paid to the time of day at which learning occurs. Consistent with this dynamic view, Shannon et al. (2013) reported that resting-state functional connectivity patterns vary between morning and evening and that the accumulation of synaptic activity over the course of wakefulness progressively modifies communication between brain regions²⁴. Circadian changes in cortisol secretion have been shown to influence neuroplasticity, with elevated cortisol levels inhibiting LTP-like plasticity in the human motor cortex²⁵. At the behavioural level, Gueugneau et al. (2015) showed that motor prediction is more efficient in the afternoon than in the morning, and that this efficiency is modulated by prior physical activity, highlighting a state-dependent regulation of motor computations²⁶. In addition, motor learning acquired in the afternoon appears to be better consolidated, whereas motor memories acquired in the morning seem more fragile and less stable over time²⁷.

Taken together, these findings suggest that the mechanisms underlying adaptation may vary with the system's current state, leading to differences in how sensorimotor information is processed, internal models are updated, and motor memories are stabilised over time. In this context, daily fluctuations may influence not only overall adaptation performance but also the specific processes that contribute to adaptive behaviour. Thus, the present study aimed first to determine whether motor adaptation varies as a function of time of day, and second to determine whether potential time-of-day effects differentially influence the explicit and implicit processes underlying adaptation. To address these questions, we designed three complementary

experiments. The first experiment investigated overall motor adaptation under conditions that allowed the co-expression of explicit and implicit processes. The second and third experiments were designed to selectively isolate and examine explicit and implicit adaptation, respectively.

Motivated by evidence for enhanced motor learning, more efficient internal model updating, and favorable neurophysiological states in the afternoon, we hypothesized that motor adaptation would be facilitated later in the day, yielding faster and/or greater adaptation than in the morning. We further predicted that time of day would differentially affect explicit and implicit processes, reshaping their relative contributions to adaptive behavior.

RESULTS

Ninety-six (n=96) healthy adults participated in three experiments using a visuomotor adaptation task commonly employed in similar studies^{10,28}. The task consisted of three successive phases: an unperturbed *baseline*, an *adaptation* phase with a 45° counterclockwise (CCW) visuomotor rotation, and an *aftereffect* phase assessing residual adaptation after the removal or alteration of standard visual feedback.

The experiments were carried out in the morning (10 a.m.) and the afternoon (3 p.m.).

All participants completed questionnaires measuring sleep quality (Pittsburgh Sleep Quality Index)²⁹ and chronotype (Morningness–Eveningness Questionnaire of Horne and Östberg)³⁰.

EXPERIMENT 1: Adaptation is faster in the afternoon

In the first experiment, we investigated how time of day affects visuomotor adaptation, focusing on the relative contributions of implicit and explicit processes. Thirty-four (n=34) participants were divided into two groups (Fig. 1a) and completed the experiment either at 10 a.m. (G10, n=17) or at 3 p.m. (G3, n=17). Independent two-sample t-tests revealed that neither chronotype (G10=53.53±5.06; G3=51.18±5.26; $t(32) = -1.33$, $p = 0.193$, $d = -0.456$) nor sleep quality the night before the experiment (G10 = 5.19±3.21; G3 = 4.00±1.84) differed significantly between the two groups.

The task required accurate pointing movements toward eight targets arranged in a circle (Fig. 1b). There were three phases: the *baseline* phase with no visual deviation of the cursor, followed by an *adaptation* phase with a 45-degree counterclockwise (CCW) deviation, and finally the *aftereffect* phase, during which visual feedback was blocked at the target location (error clamp). To separate implicit and explicit processes of adaptation, participants were asked, every three trials, to verbally indicate the number they aimed for—ranging from 0 (the target itself) to ±31, marked in ±5.625° increments on either side of the target—to compensate for the visuomotor rotation and place the cursor accurately on the target (Fig. 1c). This method allows separation of explicit strategy use—by converting the reported number into aiming angles—from implicit adaptation, defined as the difference between the hand angle and the reported aiming angle¹⁰.

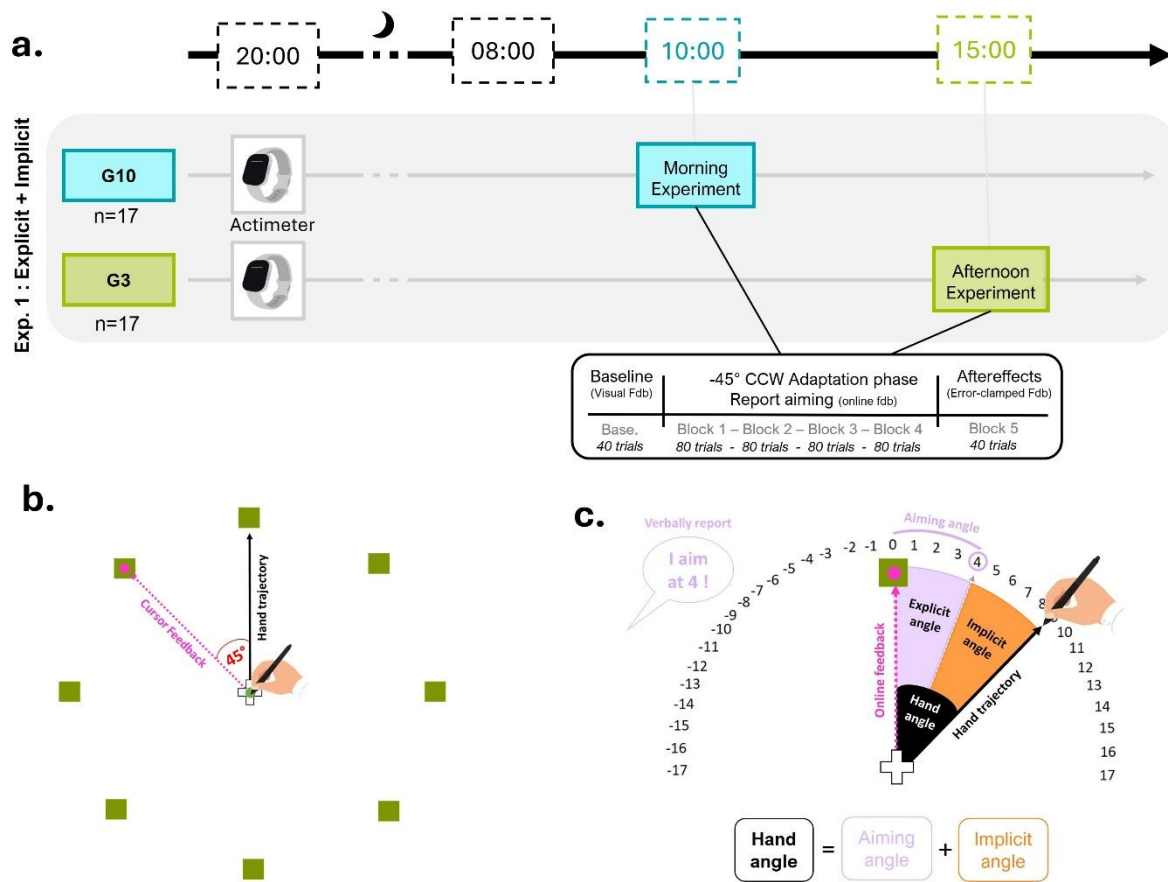


Figure 11. Setup of Experiment 1. (a) All participants completed the experiment either at 10 a.m. (G10) or 3 p.m. (G3). Each session comprised a baseline phase (40 trials) with veridical online feedback, an adaptation phase (320 trials) with online cursor feedback rotated 45° counterclockwise, and an aftereffect phase (40 trials) with error-clamped online feedback (i.e., feedback locked to the target). (b) Spatial arrangement of the 8 targets used in the visuomotor adaptation task. At the start of the adaptation phase, the cursor is rotated 45° CCW relative to the hand trajectory. By the end of adaptation, participants compensate for this perturbation by aiming approximately 45° in the opposite (clockwise) direction. (c) Experimental paradigm of the ‘report aiming’ method. Every 3 trials, participants verbally reported the aiming angle (the number displayed in a circle), reflecting the explicit process of adaptation (purple angle). Hand angle (black angle) was measured relative to the target (0°). Implicit angle (orange angle) was calculated as the difference between the hand angle and the aiming angle.

Overall visuomotor adaptation

Figure 2a shows, on a trial-by-trial basis, the mean ($\pm$ SD) hand angle ($^{\circ}$) for the G10 and G3 groups across the baseline, adaptation, and aftereffect phases. Baseline performance did not differ significantly between groups ($t(32)=-1.99$, $p=0.06$, $d=0.363$). For the adaptation phase (blocks 1-4) and the aftereffect phase (block 5), a rmANOVA revealed significant main effects of *Block* ($F(1.765) = 110.408$, $p < 0.001$, $\eta^2 = 0.619$) and *Group* ($F(1) = 5.621$, $p = 0.024$, $\eta^2 = 0.034$), as well as a significant *Group* $\times$ *Block* interaction ($F(1.765) = 6.024$, $p = 0.006$, $\eta^2 = 0.034$). Holm-corrected *post hoc* comparisons showed that G3 exhibited significantly greater hand angle values ($p<0.001$) than G10 during the early phase of adaptation (block 1 Fig. 2b). In both groups, early adaptation differed significantly from the other adaptation blocks (block 1 vs. blocks 2-4; overall, $p<0.001$). However, early adaptation differed significantly from the aftereffects in the afternoon group (block 1 vs. block 5; $p<0.001$), but not in the morning group ($p>0.1$). Blocks 2-4 did not differ from one another within either group, nor between groups ($p>0.1$). Aftereffects differed significantly from adaptation in both groups (block 5 vs. blocks 2-4; $p<0.01$). Finally, no significant between-group difference was observed during the aftereffects (block 5; $p>0.1$).

Overall, these findings indicate that motor adaptation emerged more rapidly in the afternoon than in the morning. However, this early advantage did not persist during late adaptation, as both groups reached a similar asymptotic level. Consistent with this pattern, aftereffects were comparable across groups, suggesting similar retention.

We further quantified overall adaptation by fitting hand-angle data with a classical state-space model⁵. Group differences in the retention (a) and learning (b) parameters were assessed using Mann-Whitney U tests. Retention did not differ between groups ($G10 = 0.998 \pm 0.002$; $G3 = 0.994 \pm 0.016$; $U = 146$; $p = 0.972$; $r = 0.010$). In contrast, the learning parameter was significantly higher in the afternoon than in the morning group ($G10 = 0.035 \pm 0.021$; $G3 = 0.115 \pm 0.113$; $U = 232.5$; $p = 0.003$; $r = 0.609$). Thus, while motor memory retention was comparable across groups, error sensitivity was greater in the afternoon, consistent with faster motor adaptation.

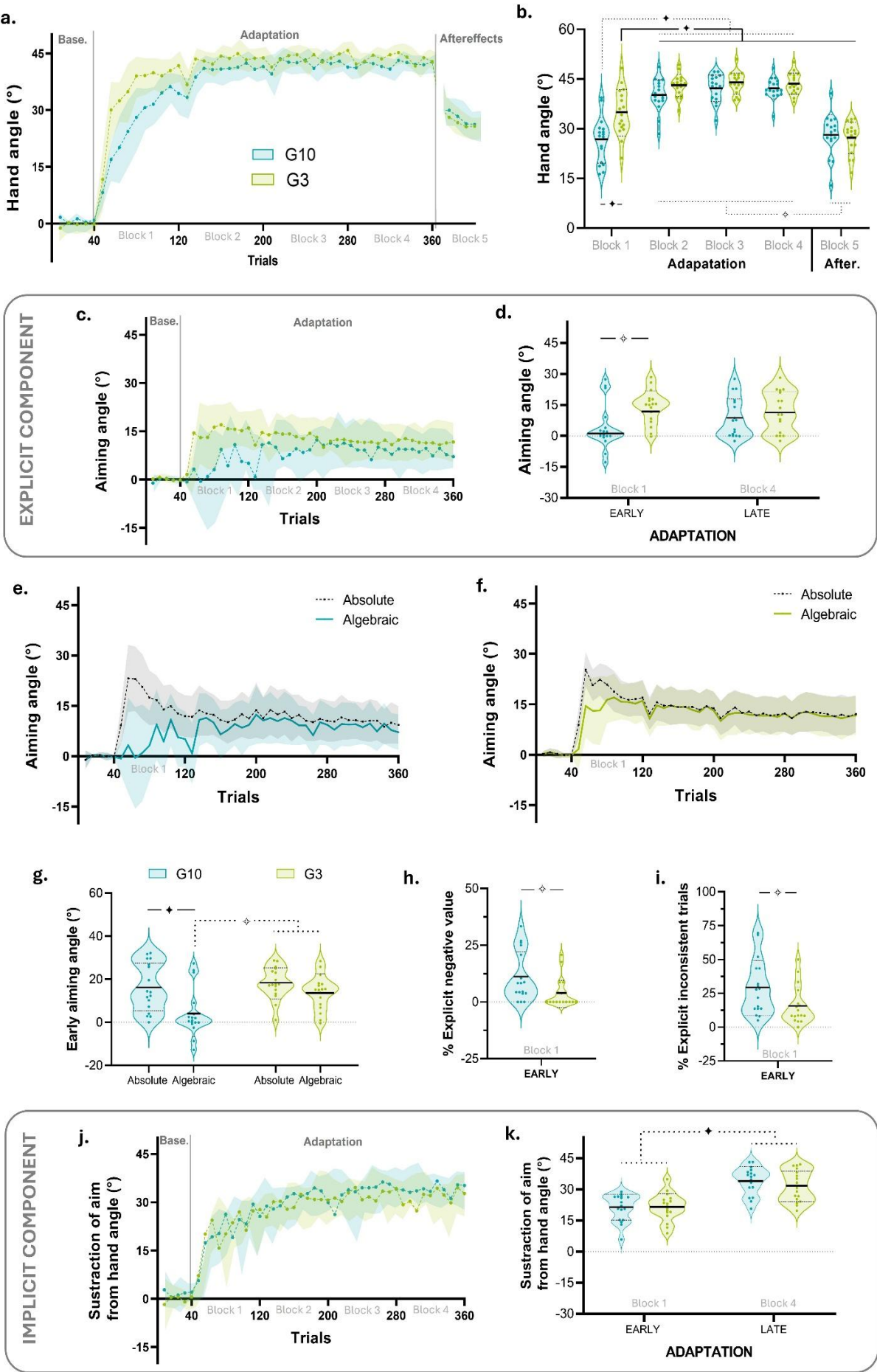


Figure 2. (a, b) Overall adaptation. (a) Trial-by-trial mean ($\pm$ SD) hand angle throughout for the G10 and G3 groups. Each dot represents one epoch (i.e., the mean of 8 trials, one trial per target). Hand angle was analysed during the baseline phase (40 trials), the adaptation phase (blocks 1 to 4; 80 trials per block), and the aftereffects phase (40 trials). **(b)** Mean hand angle ($\pm$ SD) for blocks 1 to 5 for the G10 and G3 groups. **(c-i) Explicit process of adaptation. (c)** Trial-by-trial mean ($\pm$ SD) aiming angle during the baseline and adaptation phases for the G10 and G3 groups. **(d)** Mean ($\pm$ SD) aiming angle for early (block 1) and late (block 4) explicit adaptation for both groups. **(e)** Trial-by-trial mean ($\pm$ SD) aiming angle across 'Adaptation Session' for the G10. The dashed line indicates the aiming angle in absolute values, whereas the blue line reflects the reported (veridical) aiming angle. **(f)** Trial-by-trial mean ($\pm$ SD) aiming angle across 'Adaptation Session' for the G3. The dashed line indicates the aiming angle in absolute values, whereas the green line reflects the reported (veridical) aiming angle. **(g)** Mean ($\pm$ SD) early aiming angle (block 1) for the G10 and G3 groups, expressed in absolute and algebraic (veridical report) values. **(h)** Mean ($\pm$ SD) percentage of trials with a negative explicit value during early (block 1) for the two groups. **(i)** Mean ($\pm$ SD) percentage of inconsistent explicit trials during early (block 1) for the two groups. **(j-k) Implicit process of adaptation. (j)** Trial-by-trial mean ($\pm$ SD) implicit angle (i.e., subtraction of aiming from hand angle) during the baseline and adaptation phases for the G10 and G3 groups. **(k)** Mean ($\pm$ SD) implicit angle for early and late explicit adaptation for both groups. Dots represent individual data. $\blacklozenge p < 0.001$, $\blacklozenge p < 0.05$. G10 is represented in blue, and G3 in green.

The explicit process is disturbed in the morning

Figure 2c shows trial-by-trial explicit adaptation, represented by the mean ($\pm$ SD) aiming angles for the morning and afternoon groups. Figure 2d illustrates the corresponding mean values ($\pm$ SD) for early adaptation (block 1) and late adaptation (block 4). An rmANOVA revealed a significant main effect of *Group* ($F(1) = 4.361$, $p = 0.045$, $\eta^2 = 0.100$) and a significant *Group* $\times$ *Block* interaction ($F(1) = 6.553$, $p = 0.015$, $\eta^2 = 0.028$), with no main effect of *Block* ($F(1) = 0.782$, $p = 0.383$, $\eta^2 = 0.003$). Post hoc comparisons showed greater explicit adaptation in G3 than in G10 during early adaptation ($p = 0.032$), but no significant between-group difference during late adaptation ($p > 0.05$).

Because explicit reports can be affected by sign errors³¹, whereby strategies have the correct magnitude but the wrong direction, we further analysed explicit adaptation using absolute aiming values, the percentage of negative trials, and the percentage of inconsistency, defined as trial-to-trial alternations in aiming sign.

Figures 2e and 2f show the trial-by-trial mean ($\pm$ SD) absolute and algebraic aiming angles across adaptation for the morning and afternoon groups, respectively. Figure 2g shows the corresponding mean values ($\pm$ SD) during early adaptation. The late adaptation phase is not shown for clarity, as no significant differences were observed (absolute: G10 = 10.274 ± 9.760 , G3 = 12.000 ± 9.338 ; algebraic: G10 = 8.664 ± 9.616 , G3 = 11.647 ± 9.700). An rmANOVA revealed significant main effects of Aiming Type (absolute vs. algebraic; $F(1) = 19.886$, $p < 0.001$, $\eta^2 = 0.148$) and *Group* ($F(1) = 4.817$, $p = 0.036$, $\eta^2 = 0.076$), together with a significant *Group* $\times$ *Aiming Type* interaction ($F(1) = 4.186$, $p = 0.049$, $\eta^2 = 0.031$). Post hoc comparisons showed that algebraic aiming values were significantly lower in the morning group than both algebraic and absolute aiming values in the afternoon group ($p = 0.018$). By contrast, absolute aiming values did not differ between groups ($p > 0.1$). Within groups, absolute and algebraic aiming angles differed significantly in the morning group ($p = 0.032$), but not in the afternoon group ($p > 0.1$).

Figure 2h shows the mean ($\pm$ SD) percentage of trials with a negative explicit value during early adaptation for the two groups. For clarity, negative values during late adaptation are not shown, as they were nearly identical across groups and close to zero (G10 = 0.662 ± 1.474 ; G3 = 0.662 ± 1.973). A Mann-Whitney U test showed significantly more negative values in the morning group than in the afternoon group ($U = 75$; $p = 0.014$; $r = -0.481$). Figure 2i shows the mean ($\pm$ SD) percentage of inconsistent explicit trials, defined as trial-to-trial alternations in aiming sign, for the two groups. Inconsistent values during late adaptation are also omitted, as they were nearly identical across groups and close to zero (G10 = 0.679 ± 1.513 ; G3 = 0.679 ± 2.033). An independent Mann-Whitney U test showed significantly more inconsistent values in the morning group than in the afternoon group ($U = 80$; $p = 0.027$; $r = -0.446$).

Altogether, these results indicate that explicit strategies in G10 were not absent during early adaptation but were instead disrupted in their directional expression. Participants generated explicit strategies of appropriate magnitude, as reflected in the absolute aiming values, but these strategies were often expressed in the incorrect direction and were inconsistent across trials (Fig. 2e,h,i).

The Implicit process remains stable across the day

Figure 2j illustrates, on a trial-by-trial basis, the mean ($\pm$ SD) implicit-adaptation angles (i.e., the difference between the aiming and the hand angle) for both groups, and Figure 2k shows the mean implicit-adaptation angles ($\pm$ SD) for early (block 1) and late (block 4) adaptation. A rmANOVA revealed only a significant main effect of *Block* ($F(1) = 149.284, p < 0.001, \eta^2 = 0.425$), with early adaptation (block 1) inferior to late adaptation in both groups. No significant main effect of *Group* ($F(1) = 0.258, p = 0.615, \eta^2 = 0.004$) or *Group* $\times$ *Block* interaction was observed ($F(1) = 2.321, p = 0.137, \eta^2 = 0.007$).

EXPERIMENT 2: No difference for the isolated explicit adaptation

The aim of the second experiment was to isolate the explicit process of adaptation and to observe any differences between the morning and afternoon groups. To this end, endpoint visual feedback for pointing was presented 800 ms after movement completion using a delayed feedback paradigm³², thereby minimising implicit adaptation (Fig. 3a). Thirty-four participants ($n=34$) were divided into two groups and completed the experiment either at 10 a.m. (G10_{Expl}, $n=17$) or at 3 p.m. (G3_{Expl}, $n=17$) (Fig. 3b).

Independent two-sample t-tests revealed that neither chronotype scores (independent t-test; $G10_{Impl} = 49.41 \pm 11.24$; $G3_{Expl} = 45.47 \pm 8.07$; $t(32) = -1.17, p = 0.249, d = -0.403$) nor sleep quality (independent t-test; $G10_{Expl} = 5.59 \pm 3.08$; $G3_{Impl} = 6.18 \pm 2.58$; $t(32) = 0.603, p = 0.551, d = 0.207$) differed between the two groups.

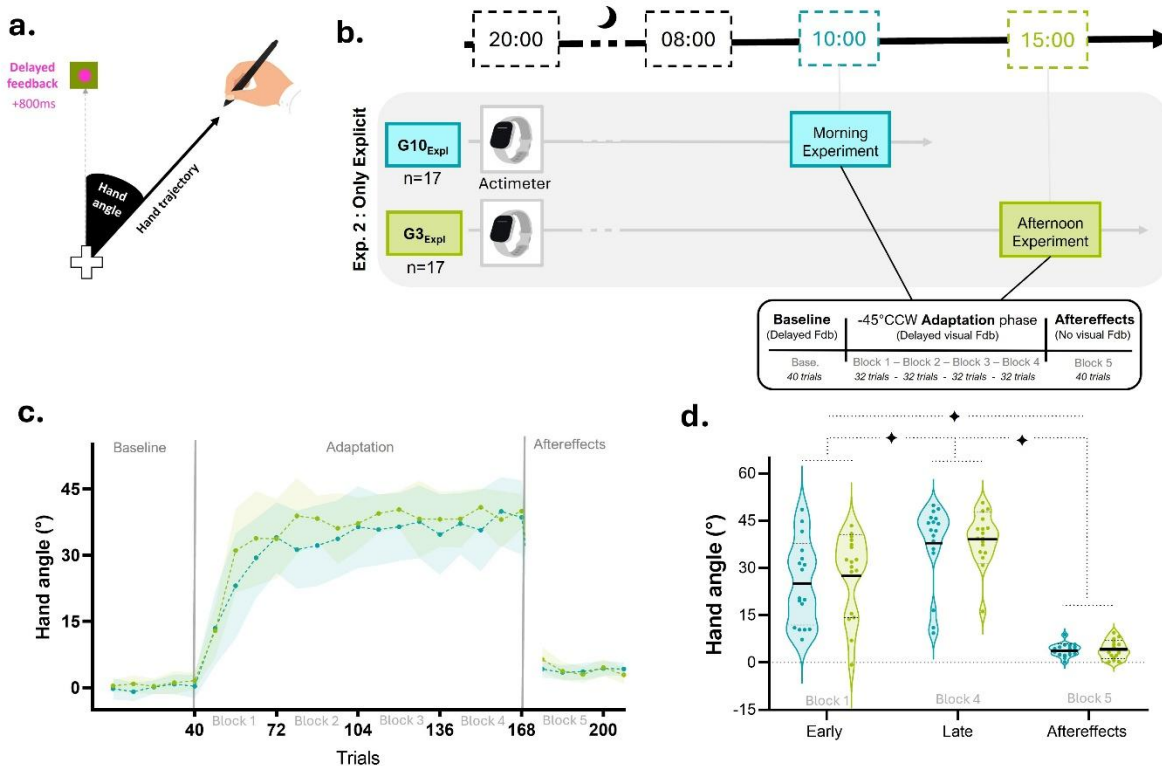


Figure 3. Experiment 2. (a) Experimental paradigm of the delayed visual feedback visuomotor adaptation task. The cursor appears 800 ms after the end of the actual movement during the baseline and 'Adaptation phase'. (b) Participants in G10_{Expl} and G3_{Expl} completed an 'Adaptation session' at 10 a.m. and 3 p.m., respectively, consisting of three phases: a baseline phase (40 trials) with end-point delayed feedback (+800ms), an adaptation phase (128 trials) with end-point delayed feedback rotated 45° counterclockwise, and an aftereffect phase (40 trials) with no feedback. To monitor sleep patterns and daily activity, all participants wore actigraphy watches starting at 8:00 p.m. the evening before the experimental sessions. (c) Mean ($\pm$ SD) hand angle throughout the 'Adaptation Session' for the G10_{Expl} and G3_{Expl} groups. Each dot represents one epoch (i.e., the mean of 8 trials, one trial per target). Hand angle was analysed during the baseline (40 trials), early and late adaptation (first and last 32 trials of the adaptation phase, respectively), and aftereffects (40 trials). (d) Mean ($\pm$ SD) hand angle during early and late adaptation, along with aftereffects for the G10_{Expl} and G3_{Expl} groups. Dots represent individual data.

Figure 3c shows, trial-by-trial, the mean ($\pm$ SD) hand angle (°) for the G10_{Expl} and G3_{Expl} groups, across the baseline phase with end-point delayed feedback, the adaptation phase with a 45° counterclockwise (CCW) rotation, and the aftereffect phase without visual feedback. Baseline performance was comparable between the morning and afternoon groups ($t(32) = 1.01$, $p = 0.320$, $d = 0.348$).

The mean ($\pm$ SD) values for early (block 1), late (block 4) adaptation (first 32 and last 32 trials of the adaptation phase, respectively), and aftereffects (block 5) are shown in Figure 3d. A rmANOVA showed a significant main effect of *Block* ($F(2) = 144.494$, $p < 0.001$, $\eta^2 = 0.687$). Post-hoc comparisons revealed that all conditions differed significantly from one another ($p < 0.001$). Hand angle was greatest during late adaptation, followed by early adaptation and the aftereffect condition. No significant main effect of *Group* ($F(1) = 0.382$, $p = 0.541$, $\eta^2 = 0.002$) or a *Group* $\times$ *Block* interaction was observed ($F(2) = 0.220$, $p = 0.803$, $\eta^2 = 0.001$). Bayesian analyses corroborated these findings, revealing evidence in favor of the absence of a *Group* $\times$ *Block* interaction ($BF_{\text{excl}} = 5.795$).

Overall, these results indicate that morning-versus-afternoon differences were no longer observed when the explicit process was isolated.

Consistent with this finding, state-space modelling of hand-angle data revealed no significant group differences in either the retention parameter a (G10_{Expl}: 0.959 ± 0.093 ; G3_{Expl}: 0.987 ± 0.023 ; $U = 139$, $p = 0.860$, $r = -0.038$; Mann-Whitney U tests) or the learning parameter b (G10_{Expl}: 0.125 ± 0.156 ; G3_{Expl}: 0.124 ± 0.097 ; $U = 165$, $p = 0.496$, $r = 0.142$; Mann-Whitney U tests). These findings suggest comparable motor memory retention and similar error sensitivity across groups.

EXPERIMENT 3: No difference for the isolated implicit adaptation

The third experiment aimed to isolate the implicit process of adaptation and assess whether it differed between the morning and afternoon. Participants were instructed to aim directly at the target while visual feedback was clamped 45° counterclockwise relative to the target direction, using a clamped visual feedback paradigm (Fig. 4a). Because the target hand angle remained constant throughout the adaptation phase, this setup eliminated the need for explicit strategies³³. Twenty-eight participants ($n = 28$) were assigned to two groups (Fig. 4b) and completed the 'Adaptation session' either at 10 a.m. (G10_{Impl}, $n = 15$) or at 3 p.m. (G3_{Impl}, $n = 13$).

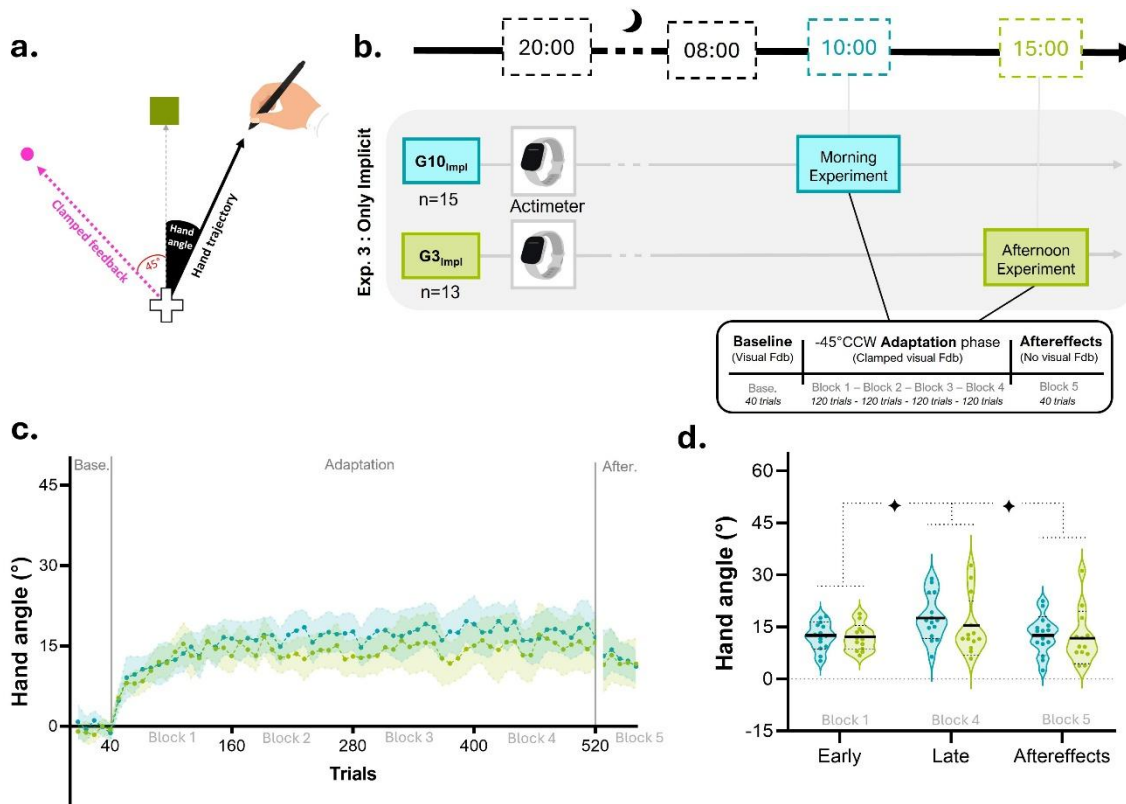


Figure 4. Experiment 3. **(a)** Experimental paradigm of the clamped visual feedback visuomotor adaptation task. During the adaptation phase, the cursor's online feedback remains constrained to a 45° CCW angle relative to the target. **(b)** Participants in G10_{Impl} and G3_{Impl} completed an 'Adaptation session' at 10 a.m. and 3 p.m., respectively. The 'Adaptation session' consisted of three phases: a baseline phase (40 trials) with no feedback, an adaptation phase (480 trials) with clamped cursor feedback, and an aftereffect phase (40 trials) with no feedback. To monitor sleep patterns and daily activity, all participants wore actigraphy watches starting at 8:00 p.m. the evening before the experimental sessions. **(c)** Mean ($\pm$ SD) hand angle throughout the 'Adaptation Session' for the G10_{Impl} and G3_{Impl} groups. Each dot represents one epoch (i.e., the mean of 8 trials, one trial per target). Hand angle was analysed during baseline (40 trials), early and late adaptation (first and last 120 trials of the adaptation phase, respectively), and aftereffects (40 trials). **(d)** Mean ($\pm$ SD) of early/late adaptation and aftereffects for both groups. Dots represent individual data.

Independent two-sample t-tests revealed that neither chronotype scores (G10_{Impl} = 51.00 $\pm$ 7.48; G3_{Impl} = 47.85 $\pm$ 9.46; $t(26) = -0.985$, $p = 0.334$, $d = -0.373$) nor sleep quality (independent t-test; G10_{Impl} = 4.60 $\pm$ 2.59; G3_{Impl} = 4.77 $\pm$ 1.64; $t(26) = 0.203$, $p = 0.841$, $d = 0.08$) differed between the two groups.

Figure 4c shows the trial-by-trial mean ($\pm$ SD) hand angle (°) for both groups across three successive phases: baseline phase with veridical visual feedback, adaptation phase with a 45° counterclockwise (CCW) rotation (clamped visual feedback), and aftereffect phase with no feedback. Baseline performance was comparable between the morning and afternoon groups ($t(26) = -0.936$, $p = 0.358$, $d = -0.355$). The mean ($\pm$ SD) values for early (block 1) and late (block 4) adaptation (first and last 120 trials of the adaptation phase, respectively), and the aftereffects (block 5) are presented in Figure 4d. A repeated-measures ANOVA revealed a significant main effect of *Block* ($F(2) = 10.890$, $p < 0.001$, $\eta^2 = 0.100$). Post hoc comparisons showed that early adaptation differed significantly from late adaptation ($p < 0.001$) and from aftereffects ($p < 0.001$). However, early adaptation did not differ significantly from aftereffects ($p = 0.829$). No significant main effect of *Group* ($F(1) = 0.409$, $p = 0.528$, $\eta^2 = 0.010$) or *Group* $\times$ *Block* interaction was observed ($F(2) = 0.520$, $p = 0.598$, $\eta^2 = 0.005$). Bayesian analyses corroborated these findings, revealing evidence in favour of the absence of a *Group* $\times$ *Block* interaction ($BF_{\text{excl}} = 3.109$).

Overall, these results indicate that, when the implicit process is isolated, adaptation does not differ between the morning and afternoon groups, consistent with the findings from Experiment 1.

Mann-Whitney U tests on the state-space model parameters revealed no significant group differences in either the retention parameter a ($G10_{\text{Impl}}$: 0.903 ± 0.254 ; $G3_{\text{Impl}}$: 0.901 ± 0.223 ; $U = 76$, $p = 0.339$, $r = -0.221$) or the learning parameter b ($G10_{\text{Impl}}$: 0.013 ± 0.016 ; $G3_{\text{Impl}}$: 0.027 ± 0.043 ; $U = 126$, $p = 0.197$, $r = 0.292$). These findings suggest comparable motor memory retention and similar error sensitivity between groups

DISCUSSION

The present study investigated whether visuomotor adaptation varies during the day and whether such variation reflects changes in explicit and/or implicit learning processes. Across three experiments, participants performed visuomotor adaptation tasks either in the morning or in the afternoon, under conditions that either allowed explicit and implicit processes to operate together or isolated them from one another. The main finding was that visuomotor adaptation was slower in the morning than in the afternoon, but only during the early phase of learning. This difference was associated with disrupted explicit strategic behaviour, characterized by incorrect aiming directions and inconsistent strategy use, whereas implicit adaptation remained largely unchanged. Importantly, when explicit and implicit processes were experimentally isolated, no morning-afternoon differences were observed. Together, these findings indicate that time of day does not simply alter the overall capacity for motor adaptation. Rather, it selectively affects the early interaction between explicit and implicit processes, revealing a previously overlooked state-dependent feature of sensorimotor learning.

Motor adaptation varies throughout the day

Motor adaptation is shaped by both external task constraints and internal states. External constraints, such as perturbation characteristics or task demands, can shape adaptation^[34,35], whereas internal states, such as ageing, mental fatigue, or increased cognitive load, have been shown to modulate overall motor adaptation^[18–20]. The present findings extend this framework by showing that time of day is another relevant internal-state variable influencing visuomotor adaptation.

Participants tested in the afternoon adapted faster than those tested in the morning. This result aligns with a broad literature showing that motor performance and motor learning are often enhanced later in the day. Maximal muscular force, sports-related performance, and more complex motor behaviours frequently peak in the afternoon or early evening^[36–38]. Similarly, previous studies showing that motor sequence learning can be better consolidated when practice occurs in the afternoon rather than in the morning, as demonstrated using the Finger Tapping Task (FTT)^{21,27}. Our results extend these observations from motor performance to the dynamics of sensorimotor adaptation. They show that the timing of learning can influence how quickly participants establish an adaptive response to a novel visuomotor perturbation.

Several physiological and neural mechanisms may contribute to this effect. Time of day is linked to fluctuations in circadian rhythms, hormonal secretion, body temperature, arousal, and wake-dependent changes in brain function^[39,40]. At the neural level, converging evidence from resting-state fMRI and fNIRS studies indicates that large-scale brain organization changes across the waking day, with progressive modifications in functional connectivity, communication, and network integration as wakefulness increases^[24,41,42]. These changes may create more favourable conditions for communication among distributed neural systems involved in sensorimotor adaptation. In this view, the afternoon advantage observed here may reflect a functional state in which the neural networks supporting strategic control, sensory prediction, and error-based updating are more efficiently coordinated.

Importantly, however, the effect of time of day was limited to early adaptation. Although participants tested in the morning adapted more slowly at first, both groups ultimately reached comparable asymptotic performance levels, and aftereffects were similar across groups. Thus, time of day did not determine whether participants could adapt, but rather how efficiently adaptation was initially established. This temporal specificity is important because early adaptation is the phase in which explicit strategies and implicit recalibration are both strongly engaged and must be coordinated to reduce errors efficiently.

Daily changes in adaptation stem from disrupted, unstable explicit strategies

The results of the first experiment indicated that a faster rate of visuomotor adaptation in the afternoon than in the morning was primarily associated with more efficient explicit strategic processes rather than with changes in implicit adaptation. This finding is consistent with the well-established role of explicit learning in supporting the fast component of sensorimotor adaptation^{5,34,35}.

Notably, the morning group did not appear to lack explicit strategies altogether. Rather, their strategies were directionally unstable. When early explicit aiming reports were analysed in absolute values, morning and afternoon groups showed comparable aiming magnitudes. This indicates that participants tested in the morning could estimate the approximate size of the required correction. However, they frequently expressed this correction in the wrong direction and alternated between opposing aiming directions across trials. Thus, the morning deficit did not reflect a failure to infer the size of the required correction, but rather a failure to consistently assign this correction to the appropriate direction.

This pattern aligns with prior work showing that participants may generate explicit corrections of appropriate magnitude while selecting an incorrect direction of compensation^[31]. Such sign errors and exploratory aiming patterns have been interpreted as markers of unstable strategic processes during visuomotor adaptation^[10,31,45]. In the present study, morning-tested participants reported more negative aiming and exhibited more inconsistent trials than afternoon-tested participants. By contrast, afternoon-tested participants displayed more stable and directionally appropriate strategies, which likely contributed to their faster early adaptation.

In state-space models, the adaptation rate is governed by error sensitivity, captured by the learning-rate parameter b . Albert et al. (2021) showed that inconsistent corrective responses across trials can reduce error sensitivity during sensorimotor adaptation^[46]. This interpretation aligns closely with our findings, as the morning group exhibited substantially more inconsistent and sign-flipped explicit responses, which may have reduced error sensitivity and thereby contributed to slower early adaptation. Interestingly, this apparent disruption of explicit processes disappeared when the explicit process was isolated in Experiment 2. Under delayed-feedback conditions, both morning and afternoon groups exhibited rapid and efficient strategic adaptation, while exploratory behaviours largely disappeared. Consistent with these behavioural results, the single-state space model revealed no significant group differences in either the retention parameter (a) or the learning-rate parameter (b). Thus, the morning effect observed in Experiment 1 cannot be attributed to a general deficit in explicit learning. Instead, it appears to reflect a context-dependent modulation of strategic control that emerges specifically when explicit strategies must be generated, evaluated, and updated online during ongoing visuomotor adaptation.

Implicit adaptation remains robust and stable across the day

In contrast to explicit strategy use, implicit adaptation was remarkably stable across the day. No significant morning-afternoon differences in implicit adaptation were observed in Experiment 1 or Experiment 3. Moreover, aftereffects, which are commonly considered to primarily reflect implicit recalibration, were comparable across groups in all three experiments.

These findings suggest that the implicit process of visuomotor adaptation is relatively insensitive to the time-of-day manipulation used in the present study.

The interpretation of implicit adaptation in Experiment 1 should be treated cautiously, as it was estimated by subtracting the reported aiming direction from the hand angle, an approach whose assumptions have recently been debated^[13,47]. However, Experiment 3 directly addressed this limitation by isolating implicit adaptation under conditions that minimized explicit strategy use. The absence of a morning-afternoon difference in this experiment strengthens the conclusion that implicit recalibration remains largely stable throughout the day.

This stability aligns with previous work describing implicit adaptation as a robust, automatic, and relatively inflexible process^[33,48], and with studies showing that it can persist despite changes in individual state, including ageing, increased cognitive load, or mental fatigue^[19,20,49,50]. Thus, time of day appears to alter visuomotor adaptation mainly through its effects on explicit strategic control and its interaction with implicit recalibration, rather than through direct modulation of the implicit process itself.

From disrupted interactions to efficient coordination: how time of day shapes explicit–implicit interactions

The principal implication of the present study is that time-of-day effects emerged only when explicit and implicit processes were co-expressed. In Experiment 1, participants tested in the morning showed slower early adaptation and less stable explicit strategies. In contrast, when explicit and implicit processes were isolated in Experiments 2 and 3, performance was comparable across morning and afternoon sessions. This pattern indicates that time of day does not primarily affect either process in isolation. Instead, it affects how these processes are coordinated during adaptation. This finding is relevant to the ongoing debate about whether explicit and implicit processes operate independently or interact during motor adaptation. Although these processes are often distinguished behaviourally and computationally, growing evidence suggests that they can share neural resources and influence one another dynamically during sensorimotor learning^[13,51–53]. The present results support this interaction view by showing that the morning impairment emerged only when explicit strategies and implicit recalibration had to operate simultaneously during ongoing visuomotor adaptation.

This interpretation is also consistent with recent neurophysiological evidence. Explicit adaptation is commonly associated with executive and cognitive processes supported by prefrontal, medial temporal, and frontoparietal networks, whereas implicit adaptation relies more strongly on cerebellar-dependent error-based learning mechanisms^[1,2,54,55]. Nevertheless, both processes recruit partially overlapping structures, including the posterior parietal cortex, premotor regions, cerebellum, and cortico-subcortical circuits involving the basal ganglia^[11,55–59].

Importantly, several studies have reported systematic changes in large-scale brain network organisation across the day. Farahani et al. (2022) observed increased connectivity of frontoparietal regions as wakefulness progressed, together with stronger integration of sensorimotor and parietal networks within the whole-brain functional architecture³⁶. Consistent with these findings, Shannon et al. (2013) and Iester et al. (2023) reported greater frontoparietal functional connectivity in the afternoon than in the morning^{24,37}. Given the established role of frontoparietal networks in executive functions such as working memory, cognitive flexibility, and strategic planning, enhanced connectivity within these networks may facilitate the generation, maintenance, and updating of explicit aiming strategies during visuomotor adaptation. At the same time, increased connectivity between posterior parietal and sensorimotor regions may support the processing of sensory prediction errors and the state-estimation mechanisms that contribute to implicit adaptation. Because the posterior parietal cortex plays a key role in visuomotor adaptation^{38–42} and has been linked to both strategic and error-based aspects of learning, stronger functional connectivity of these regions may facilitate communication between

explicit and implicit processes. Consequently, the more integrated neural architecture observed later in the day may promote a more efficient coordination between explicit and implicit processes, whereas the more segregated organisation observed in the morning may favour interference between these systems.

Beyond large-scale network organisation, fluctuations in arousal and neuromodulatory systems may also contribute to these time-of-day effects. In particular, the locus coeruleus–noradrenergic (LC-NA) system plays a central role in regulating arousal, attention, cognitive control, and neural plasticity. Pharmacological enhancement of noradrenergic transmission has been shown to improve motor learning, attention, and working memory in humans⁴³. Therefore, circadian fluctuations in noradrenergic activity may represent one potential mechanism underlying the time-of-day differences observed in explicit–implicit coordination.

Furthermore, these time-of-day variations in brain network organisation do not appear to be solely driven by endogenous circadian influences. Farahani et al. (2022) proposed that the progressive reconfiguration of functional brain networks across the day is driven, at least in part, by the cumulative impact of neural activity associated with wakefulness³⁶. Continuous engagement in daily cognitive, sensory, and motor activities may therefore promote dynamic changes in functional connectivity and network integration. Such a framework provides a plausible explanation for why explicit and implicit adaptation appeared preserved when isolated yet differed markedly when both processes were required to operate simultaneously during natural visuomotor adaptation.

Limitations and perspectives

Some limitations should be considered when interpreting the present findings. First, only two testing periods were examined, one in the morning and one in the afternoon, which prevented a detailed characterization of how visuomotor adaptation evolves across the waking day. Future studies using multiple testing sessions will be necessary to determine whether these effects change gradually across the day or follow a more specific temporal profile. Second, although our interpretation is supported by previous evidence showing daily changes in functional connectivity, network integration, and arousal, we did not collect direct neuroimaging, pupillometric, or neurochemical measures. Thus, the proposed link between time-of-day changes in brain state and altered explicit–implicit coordination remains hypothetical and should be tested more directly. For example, future studies combining visuomotor adaptation paradigms with pupillometry, as recently demonstrated by Yokoi and Weiler⁴⁴, or with other physiological markers of arousal, could provide valuable insight into whether fluctuations in noradrenergic activity contribute to the observed time-of-day differences in explicit–implicit coordination.

Beyond these limitations, the present findings open important perspectives for motor learning and rehabilitation. In particular, future work should determine whether the enhanced adaptation observed in the afternoon is driven primarily by endogenous circadian factors or by the cumulative effects of wakefulness and daily cognitive, sensory, and motor activity. Manipulating participants' level of activity before testing or comparing adaptation following different durations of wakefulness could help disentangle these contributions. Future studies should also determine whether similar time-of-day effects occur in older adults or neurological populations. This question is particularly relevant for rehabilitation, where motor training depends on repeated practice and adaptive learning. If the timing of practice influences the coordination between explicit and implicit processes, scheduling training sessions at optimal times of day could help improve the efficiency of motor adaptation.

Overall, these findings identify time of day as a previously overlooked determinant of visuomotor adaptation and suggest that the timing of practice shapes not only how much individuals learn, but how explicit and implicit learning processes are coordinated during early adaptation

MATERIALS AND METHODS

This study investigated whether visuomotor adaptation varies throughout the day and whether explicit and implicit processes are differentially affected by time of day. Three complementary experiments were conducted. Participants completed the tasks either in the morning (10:00 a.m.) or in the afternoon (3:00 p.m.). Experiment 1 assessed adaptation under conditions allowing the co-expression of explicit and implicit processes, whereas Experiments 2 and 3 isolated explicit and implicit adaptation, respectively.

Participants

The study comprised three experiments and recruited 96 healthy volunteers—36 males and 60 females (age range: 18-35 years; mean age: 22.61 ± 4.44 years). All participants were right-handed (mean Edinburgh Handedness Questionnaire score 87.56 ± 3.24)⁴⁵ and reported no neurological or psychiatric disorders. They were unaware of the experiment's purpose and had no prior experience with visuomotor adaptation tasks.

In all experiments, participants were divided into two groups: the morning group (G10), which completed the task at 10:00 a.m., and the afternoon group (G3), which completed it at 3:00 p.m. In the first experiment (Explicit + Implicit), 34 participants were randomly assigned to G10 ($n = 17$, 11 females, mean age: 22.41 ± 4.82 years) or G3 ($n = 17$, 7 females, mean age: 24.71 ± 6.15 years). In the second experiment (Explicit only), 34 participants were divided into G10_{Expl} ($n = 17$, 13 females; mean age: 22.24 ± 3.23 years) and G3_{Expl} ($n = 17$, 13 females; mean age: 19.82 ± 1.98 years). Finally, in the third experiment (Implicit only), 30 participants were split into G10_{Impl} ($n = 15$, 10 females, mean age: 22.2 ± 5.52 years) and G3_{Impl} ($n = 13$, 6 females, mean age: 24.31 ± 4.94 years). In this third experiment, we excluded two outlier participants in G3_{Impl} who showed no implicit adaptation. Their mean hand angle during the late adaptation phase remained comparable to baseline performance, suggesting no measurable response to the visuomotor perturbation.

Participants refrained from alcohol and drug use and avoided strenuous physical or mental activities before or during the entire experience. We assessed participants' chronotype using the Morningness-Eveningness Questionnaire³⁰. The scores ranged from 31 to 66, corresponding to five chronotype categories: evening type (16–30), moderate evening type (31–41, $n = 16$), intermediate type (42–58, $n = 63$), moderate morning type (59–69, $n = 17$), and morning type (70–86). Sleep quality the night before the experiments was evaluated using the Pittsburgh Sleep Quality Index²⁹, which yields a global score from 0 (very good sleep quality) to 21 (poor sleep quality).

Ethics statement

The study was approved by the Ethical Review Committee of the former Université Bourgogne Franche-Comté (CER UBFC; approval no. CERUBFC-2024-04-04-013). The committee has retained its official name following the reorganization of the former Université Bourgogne Franche-Comté into Université Bourgogne Europe and Université Marie et Louis Pasteur. The study was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation.

Experimental device and procedure

General experimental device

For all experiments, participants sat in front of the experimental setup, comprising a Wacom tablet (Cintiq Pro 24", Wacom, Vancouver, WA) positioned horizontally on a table and a

Dell computer monitor (LED Dell P2214H 22", Dell Technologies Inc., Round Rock, TX, USA) mounted vertically on a custom-built wooden stand. The apparatus was designed to block the view of the tablet and the participant's hand, so only the visual feedback on the screen was visible during the task. The monitor was placed approximately 50 cm in front of the participant at eye level to ensure clear, consistent visual input. Participants' forearms rested on a foam splint, with the stylus attached to the right index finger, allowing free wrist movement for the reaching task. The experimental software was developed in Python 3.12 using the Pygame 2.6 library (Python Software Foundation, Beaverton, OR).

The motor task required precise pointing movements to eight targets arranged in a circle (Fig.1b). The visual display included a central white cross (7 mm) indicating the starting position, a green circular cursor (3 mm diameter) representing the position of the participant's index finger (the stylus), and a green square target (6 mm) indicating the target to be reached. At the start of each trial, a white ring appeared around the central starting point, indicating the distance between the stylus's position and the centre of the white cross. As participants moved the stylus towards the starting point, the ring gradually shrank, guiding their movement without revealing the stylus's exact position. When the stylus entered an invisible square zone of 5.5 cm radius around the central cross, a red cursor appeared on the screen and the ring disappeared. Once the stylus was accurately centred, the cursor turned green, indicating a stable and precise starting position. After a delay of 500 ms, the target appeared at one of eight pseudorandomised locations, spaced every 45° along an invisible circle (0, 45, 90, 135, 180, -135, -90, and -45°) centred on the starting point, at a radial distance of 5.5 cm.

Participants were instructed to perform a quick, straight "slicing" movement through the target to minimise the likelihood of online corrections. Movement trajectories were recorded at 180 Hz. As soon as the cursor crossed an invisible circular boundary (centred on the start point, with a radius of 5.5 cm), the cursor turned pink, indicating the movement's endpoint, and remained visible for 1 second. The distance between the green target and the pink cursor provided participants with feedback on their error. Cursor feedback and delay settings varied across the three experiments.

In all three experiments, the experimental task followed the same general structure and consisted of three successive phases: an unperturbed baseline phase, an adaptation phase involving a 45° counterclockwise (CCW) visuomotor rotation, and an aftereffect phase. The duration of the adaptation phase differed across experiments because each experiment was designed to analyze a different component of visuomotor adaptation. Accordingly, Experiments 1 and 2 each consisted of four adaptation blocks, comprising 80 and 32 trials per block, respectively, whereas Experiment 3 consisted of six adaptation blocks of 120 trials each. In Experiment 1, this design allowed the characterization of visuomotor adaptation under standard conditions. In Experiment 2, fewer trials were sufficient because explicit adaptation develops rapidly and reaches asymptotic performance within relatively few trials under delayed visual feedback. In contrast, Experiment 3 included longer adaptation blocks and two additional blocks because implicit adaptation develops more gradually and requires a greater amount of practice to approach a stable plateau. Thus, both the number of trials per block and the total duration of the adaptation phase were adjusted to the expected time course of the learning process investigated in each experiment. Furthermore, for all experiments, one epoch consisted of eight trials, corresponding to one reach toward each of the eight distinct target locations.

Experiment 1: visuomotor adaptation with explicit and implicit processes

Experiment 1 replicated the paradigm developed by Taylor et al. (2014) to directly assess the contributions of explicit and implicit processes to visuomotor adaptation¹⁰. The "report aiming" method involves encircling the target with 63 numbered visual landmarks (0 to -31 for CCW and 0 to 31 for CW), spaced 5.625° apart. Participants are instructed to verbally report the number they intend to aim for to counteract the visuomotor rotation and make the cursor land on

the target. This approach allows dissociation of explicit strategy (the reported aiming direction) from implicit learning, which is the difference between the final hand position and the reported strategy. Since the target can appear in various locations, the landmark ring rotates accordingly, so that the numbers increase clockwise and decrease counterclockwise relative to the target. Once participants have verbally reported their aiming direction, the numbers on the ring disappear, and they then execute the reaching movement.

After the familiarisation phase, which comprised 40 trials with online visual feedback of stylus movements, participants completed the baseline phase of 40 trials (i.e., 5 epochs of 8 trials) under the same feedback conditions, reporting their aiming direction every third trial. The visuomotor adaptation phase then comprised 4 blocks of 80 trials (i.e., 10 epochs of 8 trials) with a 45° CCW rotation. Aiming direction was again reported every third trial to minimise interference with implicit adaptation. A 30-second rest period was enforced between each block, during which participants remained in the center position. Immediately afterwards, during the aftereffects phase, participants were instructed to disengage from any strategies and aim directly at the targets. Aftereffects were measured over 40 trials (i.e., 5 epochs of 8 trials) using the "error clamped" method with online feedback at 0°, a condition in which every trial was successful. Because this procedure minimizes sensory prediction errors and maintains every trial as successful, it slows de-adaptation and enables a more reliable assessment of the persistent implicit component of visuomotor adaptation (i.e., the aftereffect)⁴⁶.

Experiment 2: explicit visuomotor adaptation

To isolate the explicit process of visuomotor adaptation, we used the "delayed visual feedback" method, which is known to prevent implicit recalibration^{32,47}. In this method, visual endpoint feedback was presented 800 ms after the movement reached the target amplitude (5.5 cm), thereby preventing integration within the cerebellum's multisensory window (<200 ms). The feedback then remained on screen for 1 s.

Participants completed the same familiarisation phase as in Experiment 1, followed by a baseline phase of 40 trials (i.e., 5 epochs) without rotation and with delayed endpoint feedback. During the baseline phase, participants were explicitly informed that the cursor would be displayed only at the end of the movement, with a fixed delay. They were instructed to hold their hand at the endpoint until the feedback appeared. Explicit adaptation (i.e., the use of strategic adjustments) was measured during the visuomotor adaptation phase across four blocks of 32 trials (i.e., 4 epochs). To minimise fatigue, participants rested for approximately 30 seconds between blocks. During the aftereffect phase, we measured aftereffects to verify the absence of implicit recalibration. Participants were instructed to disengage any strategy and aim directly at the target during a 40-trial block (i.e., 5 epochs) without visual feedback. Unlike Experiment 1, the error-clamp method was not used because participants had performed the adaptation phase under delayed visual feedback without online cursor feedback.

Experiment 3: implicit visuomotor adaptation

To isolate the implicit process, we employed the "clamped visual feedback" method developed by Morehead et al. (2017), which provides task-irrelevant feedback³³. Specifically, we provided non-contingent online feedback clamped at -45° relative to the target, with a pink cursor that remained visible for 1 second after the reaching movement. Participants were informed that the cursor was rotated by -45° relative to the target direction and that its movement was fixed, ensuring their actions would not alter its trajectory. To confirm their understanding, they performed six demonstration trials in which they could aim anywhere, demonstrating that the cursor remained fixed at -45° regardless of their actual movement. The third experiment began with the familiarisation phase, followed by the baseline phase (40 trials, i.e., 5 epochs for each) with veridical visual feedback. The implicit adaptation phase consisted of 4 blocks of 120 clamped-visual-feedback trials (i.e., 15 epochs) under the same rest conditions as in Experiments

1 and 2. Before and during the implicit adaptation, participants received instructions to ignore the cursor and to reach quickly and straight towards the target. Immediately after, aftereffects were assessed over 40 trials (i.e., 5 epochs) without visual feedback, allowing us to capture implicit changes in motor output.

Data recording and analysis

The position of the index finger (stylus) in the x and y dimensions was recorded at 180 Hz using Python 3.12 and the Pygame 2.6 library. For each trial, the hand angle was determined at the point when the cursor crossed an invisible circle of 5.5 cm radius centred on the start position. This measure was calculated as the angular difference between the hand's position and the target's position relative to the start. Positive values indicated clockwise errors, while negative values indicated counterclockwise errors.

We also recorded reaching time, which included reaction time (the period from target appearance to the cursor leaving the initial invisible square) and execution time (the period from movement onset to the cursor crossing the invisible circle with a radius of 5.5 cm). For all experiments, we excluded trials with reach times exceeding 2000ms, which accounted for less than 1% of all trials. We also excluded trials in which movement directions exceeded twice the rotation magnitude, i.e., less than -90° or greater than 90° . This accounted for less than 1% of trials.

For data analysis, we consistently averaged eight consecutive trials corresponding to the eight target positions (i.e., 8 trials = 8 distinct targets = 1 epoch). For each experiment, we calculated the mean error during the baseline phase. We then subtracted this value from the hand angle of each subsequent trial during the adaptation and aftereffect phases. To analyse the adaptation process, two stages were defined: early and late adaptation, corresponding to the first and last blocks of each adaptation phase across experiments. For Experiment 1 only, explicit adaptation (aiming strategy) was defined based on participants' verbal reports of the numbered landmark, converted into degrees by multiplying by the angular spacing between landmarks (5.625°). Implicit learning was calculated every three trials by subtracting the reported aiming angle from the actual angular hand direction.

In Experiment 1, complementary analyses of explicit adaptation (i.e. aiming angle) were performed at the trial level rather than at the epoch level. To evaluate the magnitude of explicit responses independently of their direction, aiming angle reports were first converted to absolute values on a trial-by-trial basis and then averaged within each epoch, following the same epoch-based averaging procedure used for the algebraic values. To further characterize explicit strategic behavior during early adaptation, we quantified the percentage of negative explicit values as:

$$\% \text{ Explicit negative values} = \frac{N_{\text{negative explicit trials}}}{N_{\text{total explicit trials}}} \times 100$$

We also quantified the consistency of explicit responses by calculating the percentage of inconsistent explicit trials, defined as consecutive trial pairs in which the sign of the explicit response changed. This measure was computed as:

$$\% \text{ Explicit inconsistent trials} = \frac{N_{\text{sign alternations}}}{N_{\text{consecutived trial pairs}}} \times 100$$

Statistical Analysis

An a priori G*POWER analysis for total sample size estimation (Effect size $f = 0.30$; $\alpha = 0.05$; power = 0.90; groups = 2; number of measurements = 9; correlation among the repeated

measures = 0.5), indicated 14 participants per group were sufficient for our study. To obtain more reliable and robust results and to anticipate potential data loss due to participant exclusion or inadequate task compliance, we decided to recruit 17 participants for experiments 1 and 2 and 15 for experiment 3.

All statistical analyses were performed using JASP (version 0.18; JASP Team, 2023) and GraphPad Prism (version 8.4.0, GraphPad Software LLC). The normality of data distributions and sphericity were assessed using Shapiro–Wilk ($p > 0.05$) and Mauchly’s test ($p < 0.05$), respectively.

In Experiment 1, the data (hand angle, aiming angle, and implicit angle) were normally distributed. Two-way repeated-measures ANOVAs were conducted with *Group* as a between-subjects factor (G10 vs. G3) and *Block* as a within-subjects factor (five blocks for hand angle; three blocks for aiming and implicit angles). Aiming angle data were further analysed using a two-way repeated-measures ANOVA with *Group* (G10 vs. G3) as a between-subjects factor and *Aiming-Type* (absolute vs. algebraic) as a within-subjects factor, focusing on the early phase of adaptation. Greenhouse–Geisser corrections were applied when necessary for violations of sphericity, specifically for the hand angle data in Experiment 1. Holm-adjusted post hoc tests were performed to control for multiple comparisons. Effect sizes for ANOVAs are reported as partial eta squared (η^2). Additionally, independent-samples nonparametric Mann–Whitney U tests were performed to compare groups on the percentage of trials with negative explicit values and inconsistent explicit responses during early adaptation, as these variables violated the assumption of normality. Effect sizes for these analyses were reported using the rank-biserial correlation.

In Experiments 2 and 3, the data were normally distributed. A two-way repeated-measures ANOVA was performed with *Group* (G10 or G3) as a between-subjects factor and *Block* (early/late/aftereffects) as a within-subjects factor. The assumption of sphericity was met; therefore, no correction was applied. Holm-adjusted post hoc tests were performed to control for multiple comparisons. Complementary Bayesian repeated-measures ANOVAs were conducted to further assess the absence of differences between the morning and afternoon groups. Block was entered as a within-subject factor and Group as a between-subject factor. Models were compared against the null model, and evidence for each effect was quantified using Bayes factors of exclusion (BF_{excl}). Default Cauchy priors ($r = 0.707$) were used.

For all experiments, we fitted a single-state state-space model to the trial-by-trial hand-angle data during the adaptation phase using a custom implementation in Python. The internal state evolved according to:

$$x_{n+1} = ax_n + b_{(r-x_n)}$$

where:

- (x_n) is the estimated internal state on trial (n);
- (a) is the retention factor, representing the proportion of the motor memory retained from one trial to the next;
- (b) is the error sensitivity, representing the proportion of the sensory prediction error incorporated into the internal state on each trial;
- (r) is the imposed visuomotor rotation -45°

Model parameters (a) and (b) were estimated separately for each participant by minimizing the sum of squared differences between the observed and predicted hand angles using the `scipy.optimize.least_squares` function. Initial parameter values were set to ($a=0.98$) and ($b=0.03$), with both parameters constrained to the interval $[0;1]$. Individual parameter estimates were subsequently averaged within each experimental group for statistical analyses.

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