Visually Guided Tracking on a Handheld Device: Can It Be Used to Measure Visuomotor Skill in Shift Workers?

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Objective: We introduced a new visually controlled tracking task that can be assessed on a handheld device in shift workers to evaluate time-of-day dependent modulations in visuomotor performance.

Background: Tracking tasks have been used to predict performance fluctuations depending on time of day mainly under laboratory conditions. One challenge to an extended use at the actual working site is the complex and fixed test setup consisting of a test unit, a monitor, and a manipulation object, such as a joystick.

Method: Participants followed an unpredictably moving target on the screen of a handheld device with an attachable stylus. A total of 11 shift workers (age range: 20–59, mean: 33.64, standard deviation: 10.56) were tested in the morning, the evening, and the night shift in 2-hr intervals with the tracking task and indicated their fatigue levels on visual analogue scales. We evaluated tracking precision by calculating the mean spatial deviation from the target for each session.

Results: Tracking precision was significantly influenced by the interaction between shift and session, suggesting a clear time-of-day effect of visuomotor performance under real-life conditions. Tracking performance declined during early-morning hours whereas fatigue ratings increased.

Conclusion: These findings suggest that our setup is suitable to detect time-of-day dependent performance changes in visually guided tracking.

Application: Our task could be used to evaluate fluctuations in visuomotor coordination, a skill that is decisive in various production steps at the actual working place to assess productivity.

Keywords: field study, shift work, hand function, tracking task, visuomotor coordination, sleep, time of day

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INTRODUCTION

Productivity and "real job" performance levels among shift workers have been shown to vary depending on time of day (Bjerner & Swensson, 1953; Browne, 1949; Wojtczak-Jaroszowa & Pawlowska-Skya, 1967) with a decrease during the course of the night shift and a post-lunch dip at approximately 13:00 (Folkard & Tucker, 2003; Monk, Folkard, & Wedderburn, 1996). Vidacek, Kaliterna, Radoseric-Vidacek, and Folkard (1986), for example, reported a 5% reduction of the number of manually produced capacitors in an electronics component factory during the night shift. Those diurnal fluctuations are also observed in controlled laboratory settings, such as constant routines (Duffy & Dijk, 2002), in which all kinds of cognitive performance measures show significant time-of-day effects with performance minima during early morning hours and performance peaks during the day (Buck, 1977; De Gennaro, Ferrara, Curcio, & Bertini, 2001; Jasper, Häußler, Baur, Marquardt, & Hermsdörfer, 2009; Monk et al., 1997; Petrilli, Jay, Dawson, & Lamond, 2005). Shift workers often experience sleep deprivation and circadian disruption and typically report elevated fatigue levels, which have been linked to safety problems in the working place (Folkard & Akerstedt, 2004; Lombardi, Folkard, Willetts, & Smith, 2010).

Researchers of previous studies attributed an increased risk of work accidents in particular to the night shift (Folkard & Tucker, 2003; Gold et al., 1992), but there is evidence that the morning shift also needs special attention with regard to work accidents (Nag & Patel, 1998). Time-of-day research on driving performance (measure: maintaining a stable road position) assessed in driving simulators showed deteriorations in the early morning hours (between 02:00 and approximately

08:00) and a dip occurring in the afternoon hours (Contardi, Pizza, Sancisi, Mondini, & Cirignotta, 2004; Lenné, Triggs, & Redman, 1997, 1998). Driving demands the effective coordination of information received through the eyes and the appropriate physical responses (Jasper et al., 2010). Therefore, driving can be related to tracking—a visuomotor skill that is part of our daily life also during object manipulation (Petrilli et al., 2005). Because tracking tasks tackle a multitude of important processes (visuomotor coordination, reaction time, sustained attention) that are part of various manual procedures, such tasks may also be ideal to examine efficient production at the work place (Petrilli et al., 2005).

Yet, classical tracking tasks are carried out on a workstation that consists of a screen displaying a visual signal that is modulated by the fine motor action (e.g., strength of grip force or location of the mouse cursor). Thus, information from the visual system is used to control and coordinate the hands. During tracking, eye-centered visual information must somehow be spatially updated across eye movements to be useful for future actions, and these representations must then be transformed into commands appropriate for hand motion (Crawford, Henriques, Medendorp, & Khan, 2003). There are precise spatiotemporal patterns in which the eye and hand display bidirectional interactions (Gowen & Miall, 2006). Thus, tracking tasks are used to assess visuomotor coordination, a skill considered a prerequisite for proficient performance, particularly during object manipulation (Forseth & Sigmundsson, 2003; Petrilli et al., 2005).

These visually guided tracking tasks have also been used extensively under constant conditions or in simulated shift-work studies to predict the occurrence of circadian rhythms and to detect performance fluctuations (Akerstedt, Kecklund, & Hörte, 2001; Contardi et al., 2004; Dawson & Reid, 1997; Jansen, Rutenfranz, & Singer, 1966; Jasper et al., 2010; Petrilli et al., 2005; van Eekelen & Kerkhof, 2003). In the studies using constant routines, participants were usually tested repeatedly at 2- or 3-hr intervals during extended wakefulness over at least 17 hr under laboratory conditions. The simulated shift work studies tested performance of non–shift workers in simulated shifts in the laboratory either during consecutive night shifts (Dorrian et al., 2003) or in a simulated shift rotation with 2 day and 2 night shifts (Reid & Dawson, 2001). These studies showed that visuomotor tracking performance depends significantly on time of day with improving performance during the day and with deteriorations across the night hours, mostly starting after 22:00 (Dorrian et al., 2003; Reid & Dawson, 2001; van Eekelen & Kerkhof, 2003; Petrilli et al., 2005). Performance minima were observed either around 02:00 to 04:00 (Petrilli et al., 2005; Jasper et al., 2010) or in the morning hours between 07:00 or 08:00 (Reid & Dawson, 2001; van Eekelen & Kerkhof, 2003). Jasper et al. (2010), for instance, found a circadian rhythm in grip-force tracking under constant routine conditions that fit a sine curve and showed a minimum of performance at around 4:00 in the morning. It has also been reported that visuomotor tracking is highly sensitive to fatigue (Bohnen & Gaillard, 1994; Dawson & Reid, 1997; Petrilli et al., 2005) and that performance levels depend on age (Reid & Dawson, 2001).

An actual application of a tracking task in the industry is the occupational performance safety test (OSPAT) that is established as a fitness-for-duty measure in the shift work context. It has been introduced in a variety of industries in Australia, Brazil, New Zealand, and Malaysia and consists of a computer workstation with a standard trackball (Petrilli et al., 2005). Participants have to keep a randomly moving target in the center of three concentric circles. It has been reported that OSPAT captures subtle performance changes; in a simulated shift rotation, performance decreased across night shifts and increased across day shifts in the elder subjects (Reid & Dawson, 2001), and it is sensitive to the factor fatigue under sustained wakefulness of 24 hr (Dawson & Reid, 1997; Petrilli et al., 2005).

In all these studies, tracking has been carried out in a laboratory setting, and it remains unclear how visuomotor coordination is affected in people's daily life when they work shifts, even though the findings may be particularly relevant to ensure constant production for tasks that include hand–eye coordination.

In the present study, we introduced a two-dimensional visually guided tracking task in which participants were instructed to follow a red unpredictably moving target on a handheld device with the tip of a stylus. Hence, this tracking task demands visual perception, central processing, and fine motor control. Reaction time is part of the task because the target is moving unpredictably. Yet, it is suitable for on-site testing, allowing the assessment of tracking performance in a real-life environment because this method is mobile and can be transferred onto all typical mobile devices. Our goal was to measure visuomotor skills in a highly sensitive and reliable way with low financial and organizational costs. If suitable, such method would allow performance assessment in a high number of participants with relatively low effort and resources.

Here, we investigated whether this modified tracking task (handheld device, small screen, stylus) could be used to detect diurnal fluctuations in hand–eye coordination in shift workers working in rotating schedules (morning, evening, and night shifts).

METHODS

Participants

Eleven volunteers (2 female) aged 20 to 59 years (mean = 33.63, standard deviation [*SD*] = 10.56 years) were analyzed. All participants were right-handed as assessed with the short version of the Edinburgh Handedness Inventory (LQ > 0; Oldfield, 1971). Originally, 13 participants were part of the study, but we had to exclude 2 participants because of missing data in single sessions (a session is defined as one of four tests during each shift; see the following section). Inclusion criteria were established a priori: Participants worked in shifts for at least 3 years, had a full-time employment, were without any confirmed diagnosis of neurological or psychiatric disorders, had a normal or corrected-to-normal vision, and had no absences planned during the study period. Participants were informed that they could withdraw from the study at any time. The study was approved by the Ethics Committee of the Department of Psychology of the Ludwig-Maximilan-University, Munich, Germany, and was in accordance with the Helsinki Declaration (last updated in Seoul, 2009).

Procedure

We assessed fine motor performance during the morning, evening, and night shifts over 3 weeks (September 21–October 16, 2009). In order to familiarize participants with the tasks and the testing device, but also to minimize practice effects, subjects attended a 2-hr training period during the week prior to the study beginning, in which three test sessions were performed. During the training phase, participants also received general information on the nature of the study, sleep logs (see the Materials section), and the organizational details. We assessed the visuomotor tracking task and surveyed subjective fatigue with visual analogue scales. In the shift work test protocol, one session lasted 15 min, starting with the tracking task (lasting approximately 1.5 min), followed by the assessment of subjective fatigue (lasting few seconds), and then followed by additional tasks, which are not further specified here (handwriting, psychomotor vigilance test, task switching). All participants underwent four test sessions during the morning shift (05:55–14:05), evening shift (13:55–22:05), and night shift (21:55–06:05) at fixed 2-hr intervals. The test sessions started at 06:40 during morning shifts, at 14:40 during evening shifts, and at 22:40 during night shifts. Participants, monitored by the investigators, performed the tasks at their workplace, with their colleagues and supervisors being informed beforehand so participants would not be disturbed during testing.

All participants were tested at their third day within a given shift, that is, on the third morning shift, third evening shift, and third night shift.

Shift Schedule

The study took place in two factory sites of the Siemens AG, Berlin, Germany. At Site 1 (two participants) the employees were involved in the production steps of devices for the high- and low-voltage technology (overvoltage conductors, high-voltage rectifiers) and industrial switching systems (expansion circuit breakers). At Site 2 (nine participants) special models of motors, dynamos, and generators were produced. However, the working steps, such as varnishing or melding, were similar in both sites.

TABLE 1: Schematic Representation of the Shift System Established in Site 1

Week	Sun	Mon	Tue	Wed	Thu	Fri	Sat
1	-	M	M	M*	M	M	M
2	-	E	E	N	N	N*	-
3	-	-	-	E	E	E*	E
4	N	N	N*	-	-	-	-

Note: M = morning shift, E = evening shift, N = night shift. * indicate tested shifts. For organizational reasons, two test days were possible for the night shift. Yet, all participants were only tested once for each type of shift.

Site 1 had a forward-rotating shift schedule (see Table 1), and the participants covered the shifts in this order. After Week 4, the shift schedule started with Week 1 again.

Thus, four groups of shift workers in Site 1 covered simultaneously Weeks 1 through 4 of the timetable at one point of time.

For the purpose of our study, Site 2 changed to a forward-directed shift schedule (that is, five morning shifts, two free, five evening shifts, two free, five night shifts, two free) for the duration of the study. Normally, the participants of Site 2 adhered to a self-chosen shift schedule, in which the shifts covered by the participants could either be morning and evening shifts or morning, evening, and night shifts. There was 1 week of adaptation to the new system at Site 2 before the test sessions started.

The order of the tested shifts was variable: Three participants were tested first in the morning shift, followed by the evening and the night shift. Two participants were tested first in the night shift, second in the morning shift and third in the evening shift. One participant was tested first in the night shift, followed by the evening and the morning shift. Five participants started their testing in the evening shift, followed by the night and the morning shift.

Materials

Munich ChronoType Questionnaire (MCTQ^{Shift}). In order to assess the chronotype of the participants a shift work version (see Juda, Vetter, & Roenneberg, 2013, for details) of the MCTQ (Roenneberg, Wirz-Justice, & Merrow, 2003) was used. Of the 11 subjects, 9 completed the MCTQ$^{\text{Shift}}$ with the participants' chronotypes (as defined by the temporal midpoint of the average individual sleep period, the so-called mid-sleep time) ranging between 2:13 a.m. and 7:58 a.m. (mean: 4:46 a.m., *SD*: 1:49 hr).

Sleep logs. Participants filled out daily sleep logs throughout the whole study period. Relevant for this analysis are following variables: bedtime (BT), estimated sleep latency (Sl_Lat: time between going to bed and falling asleep), and sleep offset (Sl_Off: wake-up time). From those directly assessed variables, we computed sleep duration before a test day expressed in percentage of the individual mean (i.e., Sl_Off - BT+Sl_Lat, individual mean sleep duration over the three tested shifts corresponded to 100%,) and time awake before the respective shift (i.e., time on session 1 – Sl_Off on a test day).

Assessment of subjective fatigue and tracking performance. Personal digital assistant computers (PDAs; Hewlett Packard, HP iPAQ hx2400 Family) were used to conduct all measurements. The PDAs were small (width: 76.6 mm, depth: 16.3 mm, height: 119.4 mm) and lightweight (164.4 g). Subjective fatigue was measured with visual analogue scales. The participant had to set a cursor on a line answering the question, "How tired do you feel right now?". The answer ranged from "not tired at all" on the left pole to "very tired" on the right one. For data analysis, this line was transferred into a numbered scale ranging from 0 (*not tired at all*) to 100 (*very tired*). This visual analogue scale is established for fatigue assessment (Mota & Pimenta, 2006; Winstead-Fry, 1998) and has been used in previous shift-work studies (Dorrian et al., 2003; Petrilli et al., 2005).The PDA was used to record the visuomotor movements of the tracking task. The touch screen (diagonal size: 89 mm, *x*-axis: 55 mm, *y*-axis: 72 mm) registered the position of the

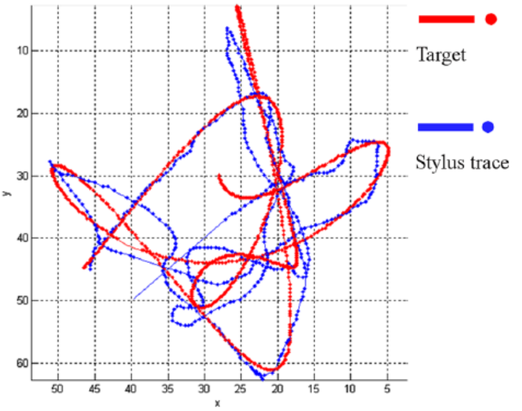

Figure 1. Exemplary graphical performance report of one 10-s trial of two-dimensional tracking: Illustrated are the target line (red line) and the participant's trace (blue line; *x*- and *y*-axes are depicted in mm).

Figure 2. Handheld device (PDA) and task execution: A red spot represented the target (lower spot), a blue spot (upper spot) provided additional visual feedback of the actual location of the stylus.

detachable stylus (size: 96 mm, barrel diameter: 4 mm, diameter of the tip: 2 mm, weight: 1 g). Sampling frequency corresponded to 90 Hz. The spatial accuracy was 0.24 mm, defined by the effective size of the display and the spatial resolution in both the *x*- and the *y*-axis (240 × 320 pixels). During the production of an irregular trajectory, this error is unsystematic, and the mean error defined as the mean deviation from the true trajectory is much smaller (estimated <0.01 mm in the current application). Spatial inaccuracies resulting from temporal processing delays would be recognizable by a mismatch between the stylus tip and the blue feedback dot. Because this was not observed and a theoretical delay would be similar across all experimental conditions, any effect on the experimental findings could be considered negligible.

See Figure 1 for an exemplary performance report.

For the tracking task, participants were instructed to follow an unpredictably moving red spot (diameter: 2 mm) on the screen with the detachable stylus. In addition to the tip of the stylus, a blue spot served as a visual feedback for the actual location of the stylus on the display. Note that participants could not see the trail, only the moving target spot and their own position spot. See Figure 2 for a visual demonstration of the task procedure

The movements of the target (the red spot) were generated by combining irregular oscillations consisting of non-harmonic sinuses along the *y*- and the *x*-axis. Following algorithms were applied:

$$\begin{aligned} y(t) &= \sin(2\pi\cdot f1\cdot t + \varphi 1) + \sin(2\pi\cdot 0.68 f1\cdot t + \varphi 2) \\ &\quad + \sin(2\pi\cdot 0.43 f1\cdot t + \varphi 3) \end{aligned}$$

$$\begin{aligned} x(t) &= \sin(2\pi\cdot f2\cdot t + \varphi 4) + \sin(2\pi\cdot 0.68 f2\cdot t + \varphi 5) \\ &\quad + \sin(2\pi\cdot 0.43 f2\cdot t + \varphi 6) \end{aligned}$$

$f1 = 1$ Hz, $f2 = 0.8$ Hz, $\varphi 1 - \varphi 6$ = random offsets between 0 and 2π.

Six trials, each lasting 10 s were performed in each session. The two-dimensional coordinates of the written paths, stored on the PDA, were transferred to a standard personal computer after the end of each session. Specialized software (Matlab; The Mathlab Works, 2000) was used to determine the distance (mm) between the center of the target point (the red spot) and the actual location of the participant`s stylus for each time point. Averaging the distance across a trial resulted in a mean tracking error. We calculated the mean performance for each session (out of the six trials) in every participant. Test-retest reliability was high, as indicated by strong positive correlations of the absolute performance scores between test sessions (Pearson correlation coefficient between sessions 3 in the morning shift and evening shift, $r > .7$, $p < .05$, $n = 11$; sessions 3 in the evening shift and night shift, $r \geq .7$, $p < .05$, $n = 11$; sessions 3 in the morning shift and night shift $r > 0.9$, $p < 0.001$, $n = 11$).

DATA ANALYSIS

Average individual performance levels were calculated for each subject as to control for interindividual baseline differences. Thus, there was an overall mean of tracking error and fatigue for each individual. This individual mean was the 100% line for each participant. Participants' performance and fatigue ratings are expressed as percentage deviation from the individual mean (100%) for analyses and graphs. Accordingly, the tracking precision and fatigue ratings were calculated with following formula:

$$\text{Precision} = 100 * \left(1 + \left(\text{overall mean ERR} - \text{session ERR} \right) / \text{overall mean ERR} \right),$$

$$\text{Fatigue} = 100 * \left(1 - \left(\text{overall mean FAT} - \text{session FAT} \right) / \text{overall mean FAT} \right),$$

in which ERR = tracking error (mm, see previous discussion) and FAT = subjective fatigue rating (0–100, see previous discussion).

The more precisely the participants followed the red target point, the higher their percentage performance. Levels greater than 100% for subjective fatigue mean that the participant was more tired than at the individual baseline level. To analyze the effects of shift and session, we used a two-factorial analysis of variance (ANOVA) for repeated measures with shift (morning, evening, night) and test session (Session 1–4) as the within-subject factor. We performed post hoc analyses of significant differences between the sessions using paired *t* tests for the corresponding sessions across the shifts. Potential sequence effects were analyzed by use of an ANOVA with the within-subject factor order (i.e., tested first, second, or third); to do so, we ranked the individual shifts according to their appearance. The training sessions were also analysed separately by an ANOVA with the within-subject factor session (1–3). Post hoc paired *t* tests were used to investigate significant differences between the sessions.

In addition to ANOVA, an *F*-tested harmonic regression was used to fit a sine function with a cycle duration of 24 h to the data, allowing for the assessment of peak phase and amplitude (CircWave V1.4, Hut, 2007, Groningen, the Netherlands). A harmonic (12 h) was added to the 24-h wave fit.

For an analysis of sleep duration before the respective shift (percentage of individual mean sleep duration) and time awake before the respective shift, we computed repeated measures ANOVAs with the within-subject factor shift. Post hoc paired *t* tests were used to analyze differences between shifts.

Data are given as a mean ± *SD*. The graph shows the percentage deviation from the mean and error bars (single standard error of the mean). For all procedures, the alpha level was set at 0.05.

RESULTS

Figure 3 shows tracking precision ($n = 11$) on a group level across morning, evening, and night shifts. The mean tracking error (mean across all participants in all sessions) corresponding to 100% was 4.49 mm, indicating that the stylus tip was 4.49 mm away from the target. Overall precision was worst during the second session of the morning shift (8:40: 94.15% = 5.85% below mean, absolute deviation = 4.75 mm) and best during the second session of the night shift (00:40: 105.21% = 5.21% above mean, absolute deviation = 4.26 mm), resulting in a maximum performance difference of approximately 11%.

The ANOVA did not reveal a statistically significant main effect of shift, $F(2, 20) = 1.07$, $p > .1$, or session $F(3, 30) = 0.98$, $p > .1$, on tracking precision. But the analysis showed a distinct pattern of precision depending on the shift and the corresponding session, interaction between shift and session, $F(6, 60) = 2.51$, $p \leq .05$. Post hoc paired *t* tests between the consecutive sessions during each shift yielded a significant performance increase ($p \leq .01$) between the test sessions at 16:40 and 18:40 during the evening shift. The remaining sessions showed no significant differences in precision between the consecutive measurements ($p > .1$).

The time course of tracking performance suggested a diurnal modulation across time of day

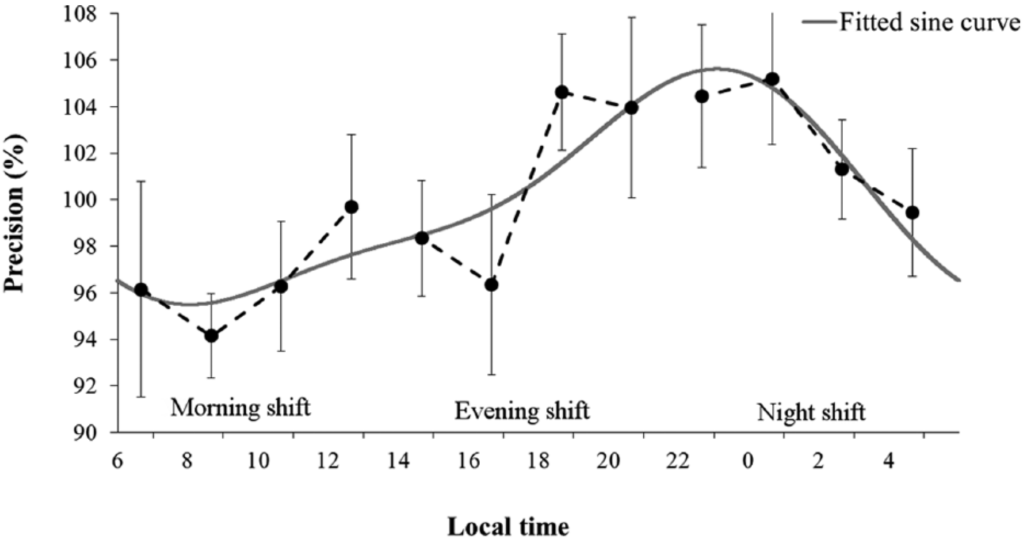

Figure 3. Precision (%) during the sessions of the shifts and a 24-hr fit with an additional 12-hr harmonic component (solid line). Bars indicate standard error (*SE*) of the mean (+/– *1 SE*).

(see Figure 3). A diurnal rhythm was documented by a statistically significant 24-hr sine function with a 12-hr component ($p < .01$), which was fit to the data averaged by time point. If the fit was performed on the individual data, it remained significant ($p < .01$). The fitted peak phase of the 24-hr rhythm was noted at 22:07, the trough was noted at 10:07, and the amplitude of the fit was 0.33 mm (representing 7.46% related to the mean level for precision). The 12-hr component of tracking precision showed an additional minimum in the afternoon hours (16:07). Refer to Figure 3 for a graphical report of the 24-hr sine function.

We did not detect an effect of testing sequence on tracking precision (ANOVA with the factor shift replaced by order, main effect of order, and interaction between order and session: $F < 1.0$, $p > .1$), indicating that performance was not influenced by the test sequence of the shifts. An analysis of the three training sessions performed a week before the actual testing revealed a significant main effect of session in the corresponding ANOVA, $F(2, 20) = 7.47$, $p \leq .01$). Post hoc paired *t* tests between the sessions showed that Session 1 differed significantly from Session 2 ($p \leq .001$) and Session 3 ($p \leq .05$), whereas Sessions 2 and 3 were indistinguishable ($p > .1$), suggesting that practice effects quickly resolved.

Subjective fatigue peaked at the end of the night shift (4:40), and a minimum was noted at 8:40. The ANOVA revealed no main effect of shift, $F(2, 20) = 1.74$, $p > .1$, but a main effect of session, $F(3, 30) = 3.58$, $p \leq .05$. Post hoc analyses between the sessions revealed that fatigue ratings were significantly lower in Session 2 than in the other sessions (all *p*s < .05). No significant interaction between shift and session was observed, $F(6, 60) = 1.34$, $p > .1$.

Although sample size was too small for further analyses, such as multiple regression approaches, a descriptive overview of sleep duration and time awake at the first test session as a function of shift is summarized in Table 2. Given that both parameters have previously been shown to have an impact on reaction time performance (Vetter et al., 2012) in a larger sample, descriptive data are shown for inferring potential interactions among tracking performance, shift, sleep duration, and time awake.

Time awake was significantly influenced by shift, $F(2,18) = 129.71$, $p < .001$. Post hoc paired *t* tests revealed significant differences between all shifts, with time awake being shortest before morning shifts and longest before night shifts. Also, relative sleep duration showed an effect of shift, $F(2,18) = 5.37$, $p \leq .05$). Post hoc paired *t* tests showed that sleep duration before morning

TABLE 2: Average Sleep Duration Before the Respective Shift (% of individual mean and in hr) and Time Awake (hr) at the First Testing Session of the Shift.

	Morning Shift	Evening Shift	Night Shift
Sleep duration, percentage (±*SD*)	87.3 (±12.89)	114.74 (±15.36)	97.76 (±14.18)
in hr (±*SD*)	5.4 (±1.44)	7.08 (±1.52)	5.9 (±1.19)
Time awake, in hr (±*SD*)	2.45 (±0.58)	5.98 (±1.67)	8.44 (±0.94)

shifts was significantly shorter than before the evening shifts.

DISCUSSION

The current study examined visuomotor coordination under field conditions in shift workers. To our knowledge, it is the first investigation that tested tracking at the actual work site during a three-shift rotation. Our results demonstrate that unpredictable tracking performance as assessed on a handheld device can detect performance fluctuations in shift workers depending on time of day. The worst tracking performance was observed during the morning shift, with a performance trough at 08:40. Mean performance increased until 12:40, followed by a second dip at 16:40. Between 16:40 and 18:40, a significant performance increase was noted. Then the curve remained on an elevated, slightly increasing level with a maximum at 00:40 during the night shift. During the consecutive sessions of the night shift, tracking performance declined. The significant interaction between shift and session indicates that the time course of precision over the sessions during the shifts was characteristic: Whereas participants exhibited an increase in performance in the last two sessions of the morning and evening shifts, a decline in the night shift starting at 02:40 was revealed.

The time window of worst tracking precision is approximately in line with reported minima in tracking or driving tasks that occur either between 6:00 and 8:00 (Contardi et al., 2004; Dawson & Reid, 1997; Reid & Dawson, 2001; van Eekelen & Kerkhof, 2003) or somewhat between 2:00 and 4:00 (Akerstedt et al., 2001; Petrilli et al., 2005; Jasper et al., 2009). Sleep duration was shortest before morning shifts, and as in previous shift work studies on psychomotor vigilance task (PVT) performance (Vetter et al., 2012), this lack of sleep may have been at least partly responsible for the reduced performance level in the early hours of the morning shift.

Our reported maximum is similar to results from van Eekelen and Kerkhof (2003), who tested tracking in a 40-hr constant routine protocol and found a maximum in tracking performance shortly before midnight at around 23:20. In addition, the time frame of best tracking precision which occurred in our study between 18:40 and 00:40, is comparable to findings from constant routine studies (Jasper et al., 2010; Petrilli et al., 2005), which found the best performance levels between 18:00 and 22:00. In studies under laboratory conditions, this interval has been referred to as the "wake-maintenance zone" (Cajochen, Münch, Knoblauch, Blatter, & Wirz-Justice, 2006; Strogatz, Kronauer, & Czeisler, 1987). In the night-shift tracking performance declined sharply after 00:40, possibly because of increasing time awake along with increasing sleep pressure, as reported before for PVT performance (Baulk, Fletscher, Kandelaars, Dawson, & Roach, 2009; Ferguson, Paech, Dorrian, Roach, & Jay, 2011; Vetter, Juda, & Ronneberg, 2012). The increasing fatigue ratings during the night shift support this assumption.

In general, it is notable, that we observed a diurnal rhythm similar to the one seen in controlled laboratory conditions (Jasper et al., 2009, 2010). Yet, we could not assess the effect of chronotype, age, or specific sleep parameters on tracking performance given the small sample size. However, it should be noted that we had a wide range of chronotypes (here: MSF [mid-sleep point on free days]: 2:13–7:58 a.m., *SD*: 1 hr, 49 min; Jasper et al., 2010: 4:01–5:07 a.m., *SD*: 25 min). In future studies we suggest a more homogenous study sample with intermediate chronotypes for investigating whether there is a shift effect. Alternatively, the study sample should be large enough to systematically analyze the effects of chronotype on time-of-day-related performance changes across shifts. One of the expectations would be that tracking precision during the early sessions of the morning shift is reduced among late chronotypes with comparison to early chronotypes.

Fatigue was modulated solely by session and was significantly lower in Session 2 compared to Sessions 1, 3, and 4. Subjective fatigue increased at the end of evening and night shifts, which could explain the increased ratings in Sessions 3 and 4; also, at the beginning of the morning shift at 6:40, participants showed high levels of subjective fatigue. We did not find a significant time course over the shifts or a shift effect for subjective fatigue, indicating that the largest effects were observed in the tracking performance. Previous investigations, however, have reported such effects for fatigue ratings (Petrilli et al., 2005; Vetter et al., 2012). Although the small study sample may have led to those nonsignificant results for the fatigue data, the tracking task revealed a significant interaction between shift and session. Tracking precision therefore seems to surpass the sensitivity of informative value of fatigue ratings in our small study sample. However, future studies linking tracking performance and productivity rates are needed to replicate the findings and to extend their ecological validity.

Important factors when assessing visuomotor performance are alterations in the test setup, for example, real driving versus simulated driving versus tracking (Bougard, Moussay, & Davenne, 2007) and the influences of writing position on handwriting performance (Jasper, Häussler, & Hermsdörfer, 2011). Established tracking tasks involve the manipulation of a joystick (Bohnen & Gaillard, 1994; van Eekelen & Kerkhof, 2003), the use of a trackball (Dawson & Reid, 1997; Petrilli et al., 2005; Reid & Dawson, 2001), grip force alteration (Jasper et al., 2010; Voelcker-Rehage & Alberts, 2007), and other tasks that demand visuomotor coordination, such as step-input pursuit tracking (Buck, 1977), rotary pursuit test (Goh, Tong, Lim, Low, & Lee, 2001), and critical eye–hand tracking capacity (Freivalds, Chaffin, & Langolf, 1983). All these tracking tasks are associated with a relative complex test setup, involving a test unit; a manipulation object, such as a joystick; and a screen. Thus, the testing unit is fixed, and the establishment of a new workstation demands organizational and financial efforts. In contrast, the tracking task presented here has a relative simple test setup. Despite the space limitation of the small screen, we found significant time-of-day effects in tracking precision. Thus, we believe that our mobile task is suitable for assessments during work time at the actual workplace.

Participants' acceptance of performing the tracking task was very high, and there were no problems with the handling qualities. However, the stylus was relatively delicate in size and diameter, in particular for men's hands. In order to increase comfort during task execution, a bigger stylus should be considered in future studies.

In further field studies, our tracking task could be particularly useful during night and morning shifts that show performance decrements and an increased risk of work accidents at the end of the night shift and in the early morning hours (Gold et al., 1992; Folkard & Tucker, 2003; Nag & Patel, 1998). The simplicity of the test setup makes it possible to test a large number of participants simultaneously, representing another advantage, especially in the shift-work context. The task could be transferred onto mobile phones—even the development of an application is conceivable.

However, future studies using a larger study sample are needed to reconfirm our results. In a first step, a laboratory investigation under controlled conditions with a homogenous study sample should be considered. In a second step, we would suggest a detailed analysis under field conditions to systematically investigate potential influences such as sleep duration, time awake, or chronotype.

In sum, the herein presented portable tracking task proved to be a sensitive measure to diurnal modulations of visuomotor coordination in our small study sample under field conditions. Future studies are needed to replicate our findings in a larger study sample and to directly link tracking precision with productivity rates to establish its predictive value. In addition, many other applications are possible such as a self-assessment of fitness before driving.

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KEY POINTS

- Visuomotor coordination is an essential part in production processes and can be evaluated through tracking tasks.
- This study introduced a new tracking task that can be assessed on a handheld device at the actual working site.
- During a three rotational shift system, time-of-day-dependent modulations in visuomotor tracking have been found.

REFERENCES

Akerstedt, T., Kecklund, G., & Hörte, L. G. (2001). Night driving, season, and the risk of highway accidents. *Sleep*, *24*, 401–406.

Baulk, S., Fletscher, A., Kandelaars, K. J., Dawson, D., & Roach, G. D. (2009). A field study of sleep and fatigue in a regular rotating 12-h shift system. *Applied Ergonomics*, *40*, 694–698.

Bjerner, B., & Swensson, A. (1953). Shiftwork and rhythm. *Acta Medica Scandinavica*, *278*, 102–107.

Bohnen, H. G., & Gaillard, A. W. (1994). The effects of sleep loss in a combined tracking and time estimation task. *Ergonomics*, *37*, 1021–1030.

Bougard, C., Moussay, S., & Davenne, D. (2007). An assessment of the relevance of laboratory and motorcycling tests for investigating time of day and sleep deprivation influences on motorcycling performance. *Accident Analysis Prevention*, *40*, 635–643.

Browne, R. C. (1949). The day and night performance of teleprinter switchboard operators. *Occupational Psychology*, *23*, 121–126.

Buck, L. (1977). Circadian rhythms in step-input pursuit tracking. *Ergonomics*, *20*, 19–31.

Cajochen, C., Münch, M., Knoblauch, V., Blatter, K., & Wirz-Justice, A. (2006). Age-related changes in the circadian and homeostatic regulation of human sleep. *Chronobiology International*, *23*, 461–474.

Contardi, S., Pizza, F., Sancisi, E., Mondini, S., & Cirignotta, F. (2004). Reliability of a driving simulation task for evaluation of sleepiness. *Brain Research Bulletin*, *63*, 427–431.

Crawford, J. D., Henriques, D. Y., Medendorp, W. P., & Khan, A. Z. (2003). Ocular kinematics and eye-hand coordination. *Strabismus*, *11*, 33–47.

Dawson, D., & Reid, K. (1997). Fatigue, alcohol and performance impairment. *Nature*, *388*, 235.

De Gennaro, L., Ferrara, M., Curcio, G., & Bertini, M. (2001). Visual search performance across 40 h of continuous wakefulness: Measures of speed and accuracy and relation with oculomotor performance. *Physiology and Behaviour*, *74*, 197–204.

Dorrian, J., Lamond, N., Holmes, A. L., Burgess, H. J., Roach, G. D., Fletcher, A., & Dawson, D. (2003). The ability to self-monitor performance during a week of simulated night shifts. *Sleep*, *26*, 871–877.

Duffy, J. F., & Dijk, D. J. (2002). Getting through to circadian oscillators: Why use constant routines? *Journal of Biological Rhythms*, *17*, 4–13.

Ferguson, S. A., Paech, G. M., Dorrian, J., Roach, G. D., & Jay, S. M. (2011). Performance on a simple response time task: Is sleep or work more important for miners? *Applied Ergonomics*, *42*, 210–213.

Folkard, S., & Akerstedt, T. (2004). Trends in the risk of accidents and injuries and their implications for models of fatigue and performance. *Aviation, Space and Environmental Medicine*, *75*, A161–A167.

Folkard, S., & Tucker, P. (2003). Shift work, safety and productivity. *Occupational Medicine (London)*, *53*, 95–101.

Forseth, A. K., & Sigmundsson, H. (2003). Static balance problem in children with hand-eye coordination problems. *Child: Care, Heath and Development*, *29*, 569–579.

Freivalds, A., Chaffin, D. B., & Langolf, G. D. (1983). Quantification of human performance circadian rhythms. *American Industrial Hygiene Association*, *44*, 643–648.

Goh, V. H., Tong, T. Y., Lim, C. L., Low, E. C., & Lee, L. K. (2001). Effects of one night of sleep deprivation on hormone profiles and performance efficiency. *Military Medicine*, *166*, 427–431.

Gold, D. R., Rogacz, S., Bock, N., Tosteson, T. D., Baum, T. M., Speizer, F. E., & Czeisler, C. A. (1992). Rotating shift work, sleep, and accidents related to sleepiness in hospital nurses. *American Journal of Public Health*, *82*, 1011–1014.

Gowen, E., & Miall, R. C. (2006). Eye-hand interactions in tracing and drawing tasks. *Human Movement Science*, *25*, 568–585.

Jansen, G., Rutenfranz, J., & Singer, R. (1966). Über eine circadiane Rhythmik sensomotorischer Leistungen [Circadian rhythms of sensorimotor performances]. *Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitspysiologie*, *22*, 65–83.

Jasper, I., Häußler, A., Baur, B., Marquardt, C., & Hermsdörfer, J. (2009). Circadian variations in the kinematics of handwriting and grip strength. *Chronobiology International*, *26*, 576–594.

Jasper, I., Roenneberg, T., Häussler, A., Zierdt, A., Marquardt, C., & Hermsdörfer, J. (2010). Circadian rhythm in force tracking and in dual task costs. *Chronobiology International*, *27*, 653–673.

Jasper, I. G. M., Häussler, A., & Hermsdörfer, J. (2011). Circadian rhythms in handwriting kinematics and legibility. *Human Movement Science*, *30*, 818–829.

Juda, M., Vetter, C., & Roenneberg, T. (2013). The Munich ChronoType Questionnaire for Shift-Workers (MCTQShift). *Journal of Biological Rhythms*, *28*, 130–140.

Lenné, M. G., Triggs, T. J., & Redman, J. R. (1997). Time of day variations in driving performance. *Accident Analysis and Prevention*, *29*, 431–437.

Lenné, M. G., Triggs, T. J., & Redman, J. R. (1998). Interactive effects of sleep deprivation, time of day, and driving experience on a driving task. *Sleep*, *21*, 38–44.

Lombardi, D. A., Folkard, S., Willetts, J. L., & Smith, G. S. (2010). Daily sleep, weekly working hours, and risk of work-related injury: US National Health Interview Survey (2004-2008). *Chronobiology International*, *27*, 1013–1030.

The Mathlab Works. (2000). MATLAB 6.1 [Computer software]. Nantick, MA: Author.

Monk, T. H., Buysse, D. J., Reynolds, C. F. 3rd., Berga, S. L., Jarrett, D. B., Begley, A. E, & Kupfer, D. J. (1997). Circadian rhythms in human performance and mood under constant conditions. *Journal of Sleep Research*, *6*, 9–18.

Monk, T. H., Folkard, S., & Wedderburn, A. (1996). Maintaining safety and high performance on shiftwork. *Applied Ergonomics*, *27*, 17–23.

Mota, D., & Pimenta, C. (2006). Self-report instruments for fatigue assessment: a systematic review. *Research and Theory for Nursing Practice, 20*, 49–78.

Nag, P. K., & Patel, V. G. (1998). Work accidents among shiftworkers in industry. *International Journal of Industrial Ergonomics*, *21*, 275–281.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97–113.

Petrilli, R., Jay, S., Dawson, D., & Lamond, N. (2005). The impact of sustained wakefulness and time-of-day on OSPAT performance. *Industrial Health*, *43*, 186–192.

Reid, K., & Dawson, D. (2001). Comparing performance on a simulated 12 hour shift rotation in young and older subjects. *Occupational Environmental Medicine*, *58*, 58–62.

Roenneberg, T., Wirz–Justice, A., & Merrow, M. (2003). Life between clocks—daily temporal patterns of human chronotypes. *Journal of Biological Rhythms*, *18*, 80–90.

Strogatz, S. H., Kronauer, R. E., & Czeisler, C. A. (1987). Circadian pacemaker interferes with sleep onset at specific times each day: Role in insomnia. *American Journal of Physiology*, *253*, 172–178.

van Eekelen, A. P., & Kerkhof, G. (2003). No interference of task complexity with circadian rhythmicity in a constant routine protocol. *Ergonomics*, *46*, 1578–1593.

Vetter, C., Juda, M., & Ronneberg, T. (2012). The influence of internal time, time awake, and sleep duration on cognitive performance in shiftworkers. *Chronobiology International*, *29*, 1127–1138.

Vidacek, S., Kaliterna, L., Radoseric-Vidacek, B., & Folkard, S. (1986). Productivity on a weekly rotating shift system: Circadian adjustment and sleep deprivation effects? *Ergonomics*, *29*, 1583–1590.

Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *The Journals of Gerontology, Series B: Psychological and Social Sciences*, *62*, 141–148.

Winstead-Fry, P. (1998). Psychometric assessment of four fatigue scales with a sample of rural cancer patients. *Journal of Nursing Measurement, 6*, 111–122.

Wojtczak-Jaroszowa, J., & Pawlowska-Skya, K. (1967). Night and shift work. *Medycyna Pracy*, *18*, 1.

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