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# Der Einfluss der Tageszeit auf die Schreib- und Trackingleistung bei Schichtarbeitern

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# Mit Genehmigung der Medizinischen Fakultät
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# Einleitende Zusammenfassung
# der schriftlichen, kumulativen Promotion

gemäß § 4a der Promotionsordnung der LMU vom 1. Juni 1983 in der zehnten

Fassung der Änderungssatzung vom 6. Juli 2012

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# 1. Zielsetzung der Untersuchungen

Für viele (senso-)motorische Leistungen konnte unter Laborbedingungen ein zirkadianer Rhythmus dokumentiert werden. Dazu gehören feinmotorische Aspekte während des Schreibens, sowie die manuelle Verfolgung von bewegten Objekten nach visuellen Vorgaben, auch als visuomotorisches Tracking bezeichnet. In der vorliegenden Untersuchung wurden diese zwei Leistungen im Feld getestet – in einem Wechselschichtsystem mit Morgen-, Tag- und Nachtschichten. Um regelmäßige Tests direkt am Arbeitsplatz mit möglichst wenig Zeitverlust zu ermöglichen, wurden diese Aufgaben auf Tablets (“Pocket-PCs“) implementiert. Dadurch war es möglich, die Teilnehmer in 2-Stunden-Intervallen während jeder Schicht in ihrem Arbeitsumfeld zu testen. Wir interessierten uns dafür, inwiefern sich der zeitliche Leistungsverlauf in diesem realen Setting von dem im Labor dokumentierten unterscheiden würde.

# 2. Einleitung und Grundlagen

## 2.1. Schichtarbeit

Ständige Verfügbarkeit und wirtschaftliche Effizienz gewinnen in unserer globalisierten Arbeitswelt kontinuierlich an Bedeutung (Vetter, Juda und Roenneberg 2012). So ist es nicht erstaunlich, dass sich dies auch auf die Arbeitsbedingungen vieler Menschen auswirkt. In der Bundesrepublik Deutschland arbeiten etwa 14 % der Erwerbstätigen in Wechselschichtsystemen, mit steigender Tendenz (Leser, Tisch und Tophoven 2013). Besonders das Gesundheitswesen ist auf die Verfügbarkeit seiner Mitarbeiter außerhalb der regulären Arbeitszeiten angewiesen, um eine 24-Stunden-Versorgung sicherzustellen (Horwitz und McCall 2004). In der Industrie wird durch den Schichtbetrieb eine volle Auslastung der Maschinen gewährleistet, was ökonomische Vorteile bietet (Folkard und Tucker 2003).

Dass insbesondere Nachtarbeit auch Gefahren mit sich bringt, zeigen zahlreiche historische Beispiele: So geschahen die Tschernobyl-Katastrophe, das Tankerunglück von Exxon Valdez, die Kernschmelze von Three Mile Island und der Chemieunfall von Bhopal in der Nacht (Folkard und Tucker 2003). Müdigkeit konnte bei einigen dieser Katastrophen als entscheidender Faktor beim Unfallhergang identifiziert werden (Rogovin und Frampton 1980; National Transport Safety Board 1990).

Eine zeitliche Abhängigkeit von Arbeitsunfällen konnte auch in einer Studie an 3470 Arbeitnehmern in der indischen Textilindustrie nachgewiesen werden. Vor allem die zweite Hälfte der Nachtschicht und der Beginn der Morgenschicht zeigten sich für Arbeitsunfälle anfällig (Nag und Patel 1998).

Darüber hinaus gibt es auch Hinweise, dass die Produktivität zu bestimmten Tageszeiten eingeschränkt ist. Untersuchungen machten deutlich, dass während der Nachtschicht nachweislich mit verminderter Effizienz und Präzision gearbeitet wurde (Vidacek, Kaliterna und Radoseric-Vidacek 1986; Folkard und Tucker 2003).

Diese Daten sind kein Zufall, denn Schichtarbeit stellt für den Organismus eine enorme körperliche und psychische Belastung dar (Kantermann 2008). Schichtarbeit ist beispielsweise ein Risikofaktor für Schlafstörungen (Moneta *et al.* 1996; Garbarino *et al.* 2002) und kardiovaskuläre Erkrankungen (Boggild *et al.* 1999; Murata *et al.* 2005). Vor allem regelmäßige Nachtarbeit gefährdet darüber hinaus die psychische

Gesundheit und schränkt das Sozialleben ein (Boucsein und Ottmann 1996; Munakata *et al.* 2001; Simões, Marques und Rocha Ade 2010).

## 2.2. Zirkadiane Rhythmen und Chronotyp

Zahlreiche physiologische Prozesse des Menschen sind einer tageszeitlichen Rhythmik unterworfen (Green, Takahashi und Bass 2008). Dazu gehören Stoffwechselprozesse, in denen Hormone wie beispielsweise das Kortisol eine Rolle spielen (Avery *et al.* 1997). Dessen pulsatile Freisetzung erreicht in den Morgenstunden zwischen 6:00 Uhr und 8:00 Uhr einen Höhepunkt (Renz 2003). Untersuchungen zeigten, dass Schichtarbeit zu Unregelmäßigkeiten in diesen hormonellen Rhythmen führen kann (Axelsson *et al.* 2003; Burch *et al.* 2005). Auch Komponenten des kardiovaskulären Systems (Herzfrequenz und Blutdruck) (Ivanov *et al.* 2007) und die Körpertemperatur unterliegen typischen tageszeitlichen Schwankungen (Kräuchi und Wirz–Justice 1994).

Grundsätzlich ist der Organismus in vielen Aspekten durch eine endogene, zirkadiane Uhr getaktet (Green, Takahashi und Bass 2008). Das bedeutet, dass selbst bei vollkommener zeitlicher Isolation mit gleichbleibenden Lichtverhältnissen nach wie vor eigenständige physiologische Rhythmen vorhanden sind. Der Schlaf-Wach-Rhythmus hat in diesen Isolationsstudien eine Dauer von etwa 24,2 Stunden (Vetter, Juda und Roenneberg 2012).

Im Alltag wird die innere Uhr durch zahlreiche Faktoren auf den 24-Stunden-Rhythmus synchronisiert. Der wichtigste Faktor ist dabei das Licht; aber auch die Außentemperatur, sowie soziale Reize (Wecker) synchronisieren die innere Uhr (Roenneberg, Daan und Merrow 2003; Roenneberg 2007).

Hinzu kommt, dass verschiedene Typen in Bezug auf die Präferenz im Schlaf-Wach-Verhalten existieren (Roenneberg, Wirz–Justice und Merrow 2003). Ein früher Chronotyp geht früh zu Bett und steht auch früher auf. Ein später Chronotyp hingegen ist abends länger aktiv und schläft in der Früh auch länger. Diese Unterschiede sind angeboren und lassen sich im Wesentlichen nicht aktiv beeinflussen. Da die Variabilität der Chronotypen bisher wenig Aufmerksamkeit in der Planung von Arbeitszeiten erhalten hat (Vetter, Juda und Roenneberg 2012), muss sich in der Realität auch ein extremer Chronotyp an die gesellschaftlichen

Konventionen in Bezug auf den Schlaf-Wach-Rhythmus anpassen, was besonders sehr späten Chronotypen häufig schwerfällt (Wittmann *et al.* 2006).

In Bezug auf die Wechselschichtarbeit bedeutet das, dass es Menschen gibt, die für bestimmte Schichten besser geeignet sind (Wittmann *et al.* 2006; Juda, Vetter und Roenneberg 2013).

Nach Entdeckung der zirkadianen Uhr wurde extensiv daran geforscht, welche weiteren Merkmale einer zirkadianen Rhythmik folgen. Diese Untersuchungen führte man im Rahmen von sogenannten „konstanten Routinen“ durch.

In konstanten Routinen wird der Einfluss von Außenreizen wie beispielsweise Licht, körperlicher Aktivität, sowie Nahrungs- und Flüssigkeitsaufnahme kontrolliert. Da auch das Schlaf-Wach-Verhalten physiologische Rhythmen beeinflussen kann, wird auch diese Komponente kontrolliert, indem die Probanden über einen Zeitraum von über 32 Stunden wach gehalten werden. Merkmale, die unter diesen kontrollierten Bedingungen periodische zeitabhängige Schwankungen zeigen, werden als zirkadian bezeichnet (Dijk, Duffy und Czeisler 1992).

Auch kognitive Leistungen standen bei diesen konstanten Routinen im Fokus: Zirkadiane Rhythmen konnten unter anderem für den Psychomotorischen Vigilanz Test (Blatter *et al.* 2006; Dijk, Duffy und Czeisler 1992; Doran, Van Dongen und Dinges 2001) und Taskwechseltest (Bratzke *et al.* 2009; Couyoumdjian *et al.* 2009) aufgezeichnet werden.

In zahlreichen Studien konnte gezeigt werden, dass auch grob- und feinmotorische Leistungen einer tageszeitlichen Rhythmik folgen. Zu den grobmotorischen Leistungen gehört beispielsweise die maximale Griffkraft, die ein Mensch aufbringen kann. Diese war zwischen 5:00 Uhr und 6:30 Uhr am geringsten, während in der Zeit zwischen 17:00 Uhr und 19:30 Uhr Spitzenwerte gemessen wurden (Stolz *et al.* 1988; Ilmarinen *et al.* 1980; Jasper *et al.* 2009a; Atkinson *et al.* 1993). Verschiedene Studien zeigten, dass die Armflexoren und Knieextensoren in ihrer Maximalkraft ebenso einen tageszeitabhängigen Rhythmus aufweisen (Gauthier *et al.* 1996; Guette, Gondin und Martin 2005).

In einem Testverfahren zur Beurteilung der manuellen Geschicklichkeit der Hand- und Fingerfunktionen, der sogenannten „Purdue Stecktafel“, konnte unter Schlafentzug ein zirkadianer Rhythmus mit einem frühmorgendlichen Leistungstief festgestellt werden. Der zeitliche Verlauf der manuellen Geschicklichkeit zeigte dabei eine positive Korrelation mit der gemessenen Körpertemperatur (Monk *et al.* 1997).

Jasper und Kollegen untersuchten im Jahr 2007 die Anpassung der Griffkräfte beim Ergreifen von Gegenständen und fanden tageszeitabhängige Schwankungen. Dabei war die Abstimmung der Griffkraft an den Gegenstand in den frühen Morgenstunden reduziert (Jasper und Hermsdörfer 2007).

Zusammenfassend kann festgehalten werden, dass für zahlreiche kognitive und motorische Leistungen tageszeitabhängige Rhythmen gefunden wurden.

## 2.3. Schreiben

Wie sich diese im Labor erhobenen Rhythmen unter Feldbedingungen verändern, war Fokus der vorliegenden Studie. Exemplarisch wurden deshalb zwei Aufgaben getestet, die bereits im Vorfeld im Mittelpunkt einiger Studien unserer Arbeitsgruppe standen: Dabei handelt es sich um Tracking und Schreiben. Im Rahmen der vorliegenden Untersuchung interessierten wir uns für den zeitlichen Verlauf dieser Leistungen in einem Wechselschichtsystem mit Früh-, Tag- und Nachtschichten.

Schreiben gehört zu den anspruchsvollsten feinmotorischen Leistungen, die im Alltagsleben routinemäßig ausgeführt werden (Blank, Miller und von Voss 2000; Rosenbaum 2009). Während der motorischen Realisation des Schreibprozesses müssen verschiedenste Bewegungen des Arms, der Hand und Finger genau aufeinander abgestimmt werden (Thomassen und Teulings 1983). Gewöhnlicherweise ist das Schreiben bei gesunden Erwachsenen derart automatisiert, dass auch weiteres Training zu keiner nennenswerten Verbesserung führen würde (Tucha *et al.* 2006b). Während bei Kindern der Prozess des Schreibens zunächst stockend verläuft, findet man bei den meisten Erwachsenen flüssige Bewegungen mit glatten Geschwindigkeitsprofilen (Rosenblum, Weiss und Parush 2003). Letzteres kann in kinematischen Analysen begutachtet werden, in denen objektive Kriterien wie Geschwindigkeit, Frequenz, Schreibflüssigkeit oder Schriftgröße zur Beurteilung herangezogen werden (Mergl *et al.* 1999; Marquardt und Mai 1994).

Die Mikrographie bei Morbus Parkinson ist ein prominentes Beispiel dafür, wie sich die Handschrift bei bestimmten neurologischen Krankheitsbildern verändern kann (Teulings und Stelmach 1991). Weit weniger bekannt ist, dass Parkinson-Patienten auch langsamer und mit reduzierter Frequenz schreiben (Tucha *et al.* 2006a). Das Gleiche gilt für das Schreibprofil bei multipler Sklerose (Longstaff und Heath 2006).

Kinematische Handschrift-Analysen wurden in der Vergangenheit auch zur Beurteilung der Schwere von extrapyramidal-motorischen Nebenwirkungen unter Antipsychotikatherapie herangezogen (Caligiuri *et al.* 2010). Typische Veränderungen zeigt auch das Schreibprofil von Patienten mit Schreibkrampf – eine Störung, die den tätigkeitsspezifischen Dystonien zugerechnet wird. Kinematische Analysen zeigten, dass es während des Schreibvorgangs bei diesen Patienten zu einer Reduktion von Frequenz, Geschwindigkeit und Schreibflüssigkeit kommt (Schneider *et al.* 2010; Hermsdörfer *et al.* 2011; Zeuner *et al.* 2007) – diese Parameter können sich allerdings durch spezielles, physiotherapeutisches Training normalisieren (Baur *et al.* 2009).

Der tageszeitliche Verlauf der Schreibleistung wurde bisher ausschließlich unter Laborbedingungen untersucht. Auch in diesem Fall wurden konstante Routinen genutzt, um einen potentiellen endogenen Rhythmus beim Schreiben zu demaskieren.

Jasper und Kollegen konnten in einer Studie an 19 Probanden unter 40 Stunden Schlafentzug zeigen, dass Schreibfrequenz und -geschwindigkeit in den Abendstunden ab etwa 21:00 Uhr abnehmen und um etwa 3:00 Uhr morgens ein Minimum erreichen (Jasper *et al.* 2011; Jasper *et al.* 2009b). Am darauffolgenden Tag erholte sich die Schreibleistung wieder und zeigte eine ähnliche Modulation wie am Tag zuvor, was für das Vorliegen eines zirkadianen Rhythmus spricht. In welchem Ausmaß die Schriftgröße von der Tageszeit abhängig ist, konnte bisher nicht abschließend geklärt werden. Jasper und Kollegen fanden keine Modulationen der Schriftgröße (Jasper *et al.* 2011; Jasper *et al.* 2009b). Allerdings zeigte eine ältere Studie aus dem Jahr 1978 eine Zunahme der Schriftgröße am Nachmittag und eine Reduktion nach einer Nacht Schlafentzug (Glenville *et al.* 1987). Grundsätzlich ist die Schriftgröße durch weitere Faktoren beeinflussbar. Zum Beispiel konnte in einigen Studien nachgewiesen werden, dass bestimmte Dosierungen von Substanzen wie Lachgas (Legge, Steinberg und Summerfield 1964), Alkohol (Dorrian 2003; Bartolomeo, Thiebaut de Schotten und Chica 2012) und Koffein (Miall, Reckess und Imamizu 2001; Tucha *et al.* 2006b) zu einer Steigerung der Schriftgröße führen können.

Im Rahmen der vorliegenden Untersuchung soll deshalb untersucht werden, inwieweit die feinmotorische Schreibleistung durch die Faktoren Tageszeit und Schichttyp unter Feldbedingungen beeinflusst wird.

## 2.4. Tracking

Um den zeitlichen Verlauf einer weiteren feinmotorischen Aktivität im Schichtarbeitskontext abzubilden, wurde eine Trackingaufgabe auf Tablets implementiert. Tracking ist eine visuomotorische Leistung, die eine genaue Koordination zwischen visueller Wahrnehmung und motorischer Antwort erfordert und im Alltag eine große Rolle spielt (Petrilli *et al.* 2005). Bei jeder gerichteten Bewegung eines Objekts nach visuellen Zielvorgaben wird letztendlich Tracking durchgeführt.

In der Arbeitswelt ist Tracking beispielsweise bei der Bedienung chirurgischer Instrumente von hoher Relevanz. Ergebnisse von Studien mit Laparoskopie-Simulatoren zeigten, dass die Trackingleistung von Chirurgen nach einer durchwachten Nacht abnimmt und mehr Ungenauigkeiten aufgezeichnet werden (Taffinder *et al.* 1998; Eastridge *et al.* 2003). Ein weiteres prominentes Beispiel für Tracking in der Praxis ist das Steuern eines Fahrzeugs. Dabei werden visuelle Informationen über die Umgebung verarbeitet und mit den geeigneten, motorischen Antworten während des Steuerns koordiniert (Jasper *et al.* 2010). Da es zahlreiche Hinweise zur diurnalen Abhängigkeit von Autounfällen gibt (Akerstedt, Kecklund und Hörte 2001; Lenné, Triggs und Redman 1997), wurde der zeitliche Verlauf der Trackingleistung in Fahrsimulatoren überprüft. In diesen Studien wurde die Trackingleistung anhand der Genauigkeit des Steuerns auf der Fahrbahnspur ermittelt. Die Präzision war zwischen 2:00 Uhr und 8:00 Uhr morgens am geringsten (Lenné, Triggs und Redman 1997, 1998; Contardi *et al.* 2004), was sich mit den kritischen Zeitfenstern der Unfallstatistiken deckt (Akerstedt, Kecklund und Hörte 2001; Lenné, Triggs und Redman 1997).

Wenn Tracking im Labor getestet wird, besteht der herkömmliche Testaufbau aus einem Bildschirm mit einem sich bewegenden, visuellen Ziel- oder Vorgabesignal. Über einen Mauscursor (Bohnen und Gaillard 1994), eine Steuerkugel (Petrilli *et al.* 2005), ein Steuerrad (Buck 1977) oder einen Kraftmesser (Jasper *et al.* 2010) moduliert der Proband ein Feedbacksignal möglichst nach den Vorgaben des Zielsignals. Da sich das Zielsignal unvorhersehbar verändert, sind Konzentration und schnelle Reaktionszeiten zur optimalen Bearbeitung der Aufgabe notwendig. Analog dazu muss sich ein Autofahrer dauerhaft auf die sich verändernden Begebenheiten auf der Straße konzentrieren und jederzeit reaktionsbereit sein.

Grundsätzlich ist die Koordination zwischen Hand und Auge ein komplexer Prozess, bei dem das Auge initial das Ziel lokalisiert und den Kontakt zwischen Hand und Objekt herstellt (Gowen und Miall 2006). Dann folgt das Auge dem Ziel, während oder bevor die Hand an diesem Punkt ankommt. Die visuelle Information wird dabei über ständige Augenbewegungen aktualisiert und in geeignete motorische Antworten der Hand transformiert (Gowen und Miall 2006).

Aus funktionellen MRT-Studien ist bekannt, dass es verschiedene neuroanatomische Regionen gibt, die in diesem Prozess aktiv sind (Doyon *et al.* 2002; Eliassen, Souza und Sanes 2001; Penhune und Doyon 2002). Im initialen Lernprozess einer isometrischen Trackingaufgabe zeigte sich eine erhöhte Aktivität in weit verstreuten kortikalen Regionen, unter anderem präfrontal, parietal und im sensomotorischen Kortex. Auch der Nucleus Caudatus und die gleichseitige, zerebelläre Hemisphäre zeigten signifikante Aktivitäten. Sobald die Trackingaufgabe erlernt und automatisiert war, fanden sich erhöhte Aktivitätsmuster in subkortikalen Regionen, wie dem zerebellären Nucleus Dentatus, Thalamus und Putamen (Floyer-Lea und Matthews 2004).

Die tageszeitliche Abhängigkeit der Trackingleistung wurde bisher fast ausschließlich unter Laborbedingungen untersucht. So zeigte eine Studie von Jasper und Kollegen aus dem Jahr 2010, dass isometrisches Krafttracking unter Schlafentzug einer zirkadianen Rhythmik folgt. Dabei war die Präzision in den frühen Morgenstunden am geringsten, was sich mit Ergebnissen von anderen konstanten Routinen deckt (van Eekelen und Kerkhof 2003; Jansen, Rutenfranz und Singer 1966). Besonders deutlich wurde dieser Effekt unter der zusätzlichen Belastung durch eine Gedächtnisaufgabe (Jasper *et al.* 2010).

Anwendung in der Industrie findet Tracking auch als Instrument zur Einschätzung der Leistungsfähigkeit vor Dienstantritt, in Form des sogenannten „OSPAT-Tests“. „OSPAT“ ist die Kurzform des „Occupational Safety Performance Assessment Test”, der in einer Reihe von Industrien in Australien, Brasilien, Neuseeland und Malaysia routinemäßig durchgeführt wird. Eingesetzt wird dieser Test beispielsweise im Transportwesen, in der Minenindustrie oder Metallproduktion. Letztendlich prüft der „OSPAT“ Test visuomotorische Fähigkeiten mit einer klassischen Trackingaufgabe: Dabei sitzen die Probanden vor einem Bildschirm und verfolgen über eine Steuerkugel ein sich zufällig bewegendes Ziel.

Der „OSPAT-Test“ stand im Mittelpunkt einiger Studien, die veranschaulichten, dass die visuomotorische Leistung durch Schlafentzug stark beeinträchtigt wird (Petrilli *et al.* 2005). Dawson und Kollegen demonstrierten darüber hinaus, dass ein Schlafentzug von 24 Stunden die Trackingleistung ähnlich negativ beeinflusst, wie ein Blutalkohollevel von 0,1 ‰ (Dawson und Reid 1997).

Es wurde auch der Versuch unternommen, den „OSPAT-Test“ wissenschaftlich im Schichtarbeitskontext zu validieren. Deshalb wurden Studien unter simulierten Schichtarbeitsbedingungen durchgeführt, die deutlich machten, dass die Trackingleistung während der Nachtschicht abnimmt (Dorrian *et al.* 2003), insbesondere bei älteren Probanden (Reid und Dawson 2001). Allerdings ist die Übertragbarkeit dieser Studien in die Realität aus verschiedenen Gründen fraglich: Zum einen wurden nur bestimmte Schichten getestet (7 konsekutive Nachtschichten (Dorrian *et al.* 2003), 2 konsekutive Tag- und Nachtschichten (Reid und Dawson 2001)), zum anderen waren keine Probanden mit Schichtarbeitserfahrung mit eingeschlossen. Aus diesen Gründen ist eine Untersuchung der visuomotorischen Leistung im Feld ausstehend, um die bisherigen Ergebnisse zu überprüfen und die Anwendbarkeit von derartigen visuomotorischen Tests im Schichtdienst zu validieren.

## 2.5.Fragestellung und Methode

Im Rahmen der vorliegenden Untersuchung wurde die Schreib- und Trackingleistung auf Tablets – sogenannten „Pocket-PCs“ – getestet, was eine Weiterentwicklung der bisherigen Versuchsanordnungen darstellt. Die Mobilität unseres Settings bringt viele methodische Vorteile mit sich: Nur dadurch war es möglich, eine große Anzahl von Probanden zum gleichen Zeitpunkt zu testen. Für die Durchführung der Tests war kein gesonderter Raum, kein spezieller Arbeitsplatz notwendig – die Teilnehmer konnten in ihrem realen Arbeitsumfeld getestet werden. Dies stellt eine immense Verbesserung der in der Industrie eingesetzten Leistungstests dar. Auch eine Entwicklung einer entsprechenden Applikation für Smartphones ist denkbar und könnte ohne größeren ökonomischen Aufwand umgesetzt werden.

Bisher wurde der zeitliche Verlauf feinmotorischer Leistungen hauptsächlich im Labor untersucht. Unter diesen kontrollierten Bedingungen fand man zirkadiane Rhythmen mit Leistungsminima gegen 3:00-4:00 Uhr morgens. Wie sich die Schreib- und Trackingleistung im Feld in einem 3-Schicht-System zeitlich verändert, war im Fokus der vorliegenden Studie. Wir gingen davon aus, dass neben dem Faktor Tageszeit auch die jeweilige Schicht die Leistung maßgeblich beeinflussen würde mit Leistungseinbußen insbesondere im Verlauf der Nachtschicht und in der Morgenschicht.

# 3. Zusammenfassung

Im Rahmen der vorliegenden Studie wurde untersucht, inwieweit die Faktoren Tageszeit und Schichttyp (senso-)motorische Leistungen in einem 3-Schicht-System beeinflussen. Aus Voruntersuchungen ist bekannt, dass Schreib- und Trackingleistungen unter Laborbedingungen einem zirkadianen Rhythmus mit einem Leistungstief gegen 3:00-4:00 Uhr morgens folgen. Im Fokus dieser Studie stand deshalb die Frage, wie sich der zeitliche Verlauf dieser Leistungen unter Feldbedingungen verändert: Beeinflusst der Faktor Schicht maßgeblich die (senso-)motorische Leistung oder würden sich auch im Schichtbetrieb ähnliche zeitabhängige Schwankungen wie unter Laborbedingungen ergeben?

Als Studienort wurden zwei Industriewerke der Firma Siemens in Berlin ausgewählt, in denen nach einem Wechselschichtsystem mit Morgen, Tag- und Nachtschichten gearbeitet wurde. Von September bis Oktober 2009 wurden Schichtarbeiter von einem Studienteam mit Beteiligung der Doktorandin betreut und während des Schichtbetriebs in 2-Stunden-Zeitintervallen getestet. Die Schreib- und Trackingaufgabe wurde aus methodischen Gründen auf Tablets (“Pocket-PCs“) implementiert. Dadurch konnte gewährleistet werden, dass die Probanden simultan in ihrem realen Arbeitsumfeld getestet wurden.

Die Schreibgeschwindigkeit (n=34) war durch den Faktor Schicht und durch die Tageszeit mit einem deutlichen Leistungstief zu Beginn der Morgenschicht um 6:40 Uhr moduliert. Insgesamt war die Geschwindigkeit in der Morgen- und Nachtschicht reduziert. Analog dazu war die Schriftgröße (n=34) durch den Faktor Schicht beeinflusst mit geringster Größe in der Morgenschicht (Minimum: 6:40 Uhr).

Für die Trackingaufgabe standen uns weniger Probanden (n=11) zur Verfügung. Es stellte sich heraus, dass die Trackingleistung durch die Tageszeit beeinflusst ist, mit einem Tief um 8:40 Uhr.

Diese Ergebnisse zeigen, dass visuo- und feinmotorische Leistungen in einem 3-Schicht-System vor allem zu Beginn der Morgenschicht beeinträchtigt sind. Wir gehen davon aus, dass die geringe Schlafdauer vor der Morgenschicht, die auch im Rahmen dieser Untersuchung erhoben wurde, dabei eine wichtige Rolle spielt.

Visuo- und Feinmotorik sind wichtige Fähigkeiten des Menschen, die im Alltag insbesondere beim Umgang mit Objekten und bei der Bedienung von Instrumenten eine Rolle spielen. Es ist naheliegend, dass unsere Daten auch hohe ökonomische

Relevanz haben, da diese Leistungen in Produktionsprozessen, in denen Präzision und Effektivität gefragt sind, von potenzieller Bedeutung sind. Darüber hinaus haben Schwankungen der fein- und visuomotorischen Leistung möglicherweise auch bei der Entstehung von Arbeitsunfällen einen Anteil. Die Aufgabe zukünftiger Studien wird deshalb sein, die Zusammenhänge zwischen (Senso-)motorik und Produktionseffektivität beziehungsweise Arbeitsunfällen zu ergründen.

# 4. Abstract

The following study investigated (visuo-)motor skills in a rotational shift system. Previous studies under laboratory conditions showed that handwriting and tracking performances followed a circadian rhythm, with a performance minimum at 3:00 or 4:00 in the morning. Therefore, this investigation assessed handwriting and tracking in a real-life setting. We investigated the time of day and shift effects of handwriting kinematics and tracking precision among shiftworkers directly at the work place.

The study took place from September to October 2009 in two factory sites of the Siemens AG in Berlin. The employees worked in a three rotational shift system with morning, evening, and night shifts. They attended tests in two-hour intervals during each shift supervised by a study team. We implemented the task on hand-held pocket PCs to allow simultanous tests directly at the work place.

Handwriting velocity (n=34) was influenced by the factor shift and time of day with a minimum of performance at the beginning of the morning shift at 06:40. During morning and night shifts handwriting velocity was significantly reduced. Similarly, script size (n=34) was modulated by the factor shift with a performance minimum at 06:40.

A smaller group of participants (n=11) performed the tracking task. Here, we found a significant influence of time of day with a performance trough at 8:40 in the morning.

In sum, the present field study reports significant modulations of visuomotor and finemotor performances in a rotational shift system. In particular, at the beginning of the morning shift, these performances were impaired.

One important factor for these deficits may have been the reduced sleep duration before morning shifts, which we also assessed during the study period

Visuomotor and fine motor control play an important role in daily life, in particular during manual object handling. Our data are potentially of economic relevance since these skills are indispensable for accurate and effective production. In addition, deficits of fine motor and visuomotor coordination may also be relevant for work accidents. We suggest for future research to systematically investigate the relationship between fine motor control and production efficiency or accident rates.

# 5. Publikation: The effects of shift work and time of day on fine motor control during handwriting

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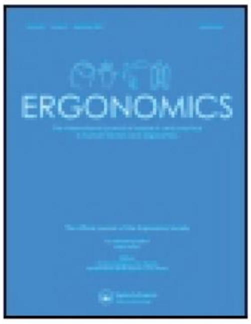

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## The effects of shift work and time of day on fine motor control during handwriting

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# The effects of shift work and time of day on fine motor control during handwriting

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Handwriting is an elaborate and highly automatised skill relying on fine motor control. In laboratory conditions handwriting kinematics are modulated by the time of day. This study investigated handwriting kinematics in a rotational shift system and assessed whether similar time of day fluctuations at the work place can be observed. Handwriting performance was measured in two tasks of different levels of complexity in 34 shift workers across morning (6:00–14:00), evening (14:00–22:00) and night shifts (22:00–6:00). Participants were tested during all three shifts in 2-h intervals with mobile testing devices. We calculated average velocity, script size and writing frequency to quantify handwriting kinematics and fluency. Average velocity and script size were significantly affected by the shift work schedule with the worst performance during morning shifts and the best performance during evening shifts. Our data are of high economic relevance as fine motor skills are indispensable for accurate and effective production at the work place.

**Practitioner Summary:** Handwriting is one of the most complex fine motor skills in humans, which is frequently performed in daily life. In this study, we tested handwriting repeatedly at the work place in a rotational shift system. We found slower handwriting velocity and reduced script size during morning shifts.

**Keywords:** field study; fine motor control; handwriting; kinematic analysis; rotating shift

## 1. Introduction

Especially the healthcare sector and the manufacturing industry rely on employees to work on 24-h schedules, expecting the quality of work output to remain consistently high throughout day and night. Human physiology, behaviour and cognition, however, are regulated by the circadian clock (Green, Takahashi, and Bass 2008; Kyriacou and Hastings 2010), leading to systematic fluctuations in bodily functions across the 24-h day.

Shift work schedules bear an increased risk of work-related accidents, particularly during the night shift (Gold et al. 1992; Folkard and Tucker 2003). An analysis of 3470 work-related accidents in the shift working industry showed that most accidents happen in the second half of the night shift and the first half of the morning shift (Nag and Patel 1998). Increases in accident rates were associated with decreased sleep duration and growing sleep pressure (Folkard and Tucker 2003; Folkard and Akerstedt 2004; Lombardi et al. 2010). In driving simulators, performance in terms of keeping lane position stable is subject to time-dependent modulations with deteriorations between 02:00 and 08:00 (Lenné, Triggs, and Redman 1997, 1998; Contardi et al. 2004). Road accident rates peak between 03:00 and 05:00, even when controlled for driving impediments such as alcohol intoxication (Lisper et al. 1979; Langlois et al. 1985; Summala and Mikkola 1994). In addition to factors such as attention, alertness and reaction time (Lisper, Laurell, and Stening 1973; Lisper, Laurell, and van Loon 1986), steering demands accurate visuomotor coordination (Contardi et al. 2004; Bougard, Moussay, and Davenne 2007). Similarly, studies that assessed surgeons' dexterity in laparascopy simulators during night shifts showed that sleep deprivation increased error rates and extended time to completion (Taffinder et al. 1998; Eastridge et al. 2003).

Research on fine motor control during shift work is scarce, despite manual dexterity playing a decisive role at various stages of manufacturing. Studies that simulated shift work conditions have shown that visuomotor tracking performance changes significantly with time of day. Performance improved during the day and deteriorated during night hours after 22:00 (Reid and Dawson 2001; Dorrian et al. 2003). Vidacek et al. (1986) reported a 5% reduction in the number of manually produced capacitors in an electronics component factory during the night shift.

As handwriting involves precise coordination of multiple arm, finger and wrist movements, fine motor control can be assessed particularly well by the study of the sensorimotor aspects of handwriting (Thomassen and Teulings 1983).

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It constitutes one of the most advanced fine motor functions of humans (Blank, Miller, and von Voss 2000), that is, nevertheless, well trained, frequently performed in everyday life and highly automatised in adult subjects (van Galen 1991; Marquardt, Gentz, and Mai 1996; van Gemmert and Teulings 2006; Rosenbaum 2009). Due to automatisation, short-term practice does not increase performance levels in skilled handwriting (Tucha et al. 2006b). Typical handwriting tasks involve the writing of words or sentences and the drawing of superimposed circles. Handwriting can be quantified in terms of kinematic parameters such as frequency (vertical strokes per second [Hz]), velocity and script size as performed in studies on writer's cramp (Baur et al. 2006; Zeuner et al. 2007), Parkinson's disease (Tucha et al. 2006a), multiple sclerosis (Longstaff and Heath 2006), depression (Mergl et al. 2004), side effects of antipsychotics (Caligiuri et al. 2010) and when evaluating training effects (Mai and Marquardt 1994; Schenk et al. 2004; Baur et al. 2009).

The few studies that examined time of day effects on handwriting were usually conducted under constant routine conditions (Baur et al. 2009; Jasper et al. 2011). Constant routine protocols unmask circadian modulations of physiological, psychological and cognitive parameters in humans. Participants usually live under constant conditions and illumination levels and the impact of rhythmic behaviours, such as sleep and physical activity, or food intake is controlled (Duffy and Dijk 2002). Our own investigations of fine motor coordination during handwriting, as assessed under 40-h constant routine conditions, revealed decreased velocity and frequency starting at around 21:00, followed by a performance minimum in the early morning hours at ca. 03:00 (Jasper et al. 2009a, 2009b). Afterwards, performance improved until noon on the second day, suggesting a circadian modulation of fine motor coordination. Whether script size is modulated by time of day remains controversial: while Glenville et al. (1987) reported enlarged script size in the afternoon and a tendency to write smaller after a night of sleep deprivation, Jasper et al. (2009a, 2009b) did not find systematic changes in script size across 40-h constant routine protocols. Decreased script size has also been observed in pathological conditions such as Parkinson's disease or multiple sclerosis (van Gemmert, Teulings, and Stelmach 2001; Longstaff et al. 2003; Longstaff and Heath 2006).

In this study we investigated handwriting kinematics during shift work related to shift type and time within shift. Furthermore, we asked the participants to fill in sleep logs during the study period in order to gain additional information on the sleep habits of the shift workers. Task characteristics, such as the complexity and length of the written trace, can affect the kinematics of routine handwriting (Mergl et al. 1999; Schneider et al. 2010). Therefore, we assessed the writing of two different basic script samples, namely superimposed circles and a simple word ('Wellen' = 'waves' in English). Since our former investigations have not revealed effects of writing task on performance changes during laboratory conditions (Jasper et al. 2009a, 2009b), we did not expect an effect of task complexity.

We tested handwriting performance on a mobile device in participants working in morning, evening and night shifts. We expected fine motor control to be influenced by the specific work shift and time of day, as suggested by studies under laboratory conditions (Jasper et al. 2009a, 2009b).

## 2. Methods

### *2.1 Participants*

The analysed study sample consisted of 34 right-handed volunteers (two female) aged 20–59 years (mean = 35.2 ± 9.6 years). Participants were included a priori if they worked in shifts for at least three 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 no planned absences during the study period. Subjects were informed that they could withdraw from the study at any time. The study has been approved by the Ethics Committee and was in accordance with the Helsinki Declaration (last updated in Seoul in 2009).

### *2.2 Procedure*

The study tested handwriting performance over three weeks (21 September–16 October 2009) during morning, evening and night shifts. In order to familiarise the participants with the task, they attended a 2-h training with three sessions prior to the study start.

We tested three sensorimotor tasks in each session, one of which was the handwriting task presented here (additional tasks: visuomotor tracking and object manipulation). We also assessed other tasks with low attentional requirements that took place before and after the sensorimotor task, but are not further specified here. Total test duration was 15 min, the handwriting task lasted 2 min. Test sessions were performed during the morning shift (05:55–14:05), evening shift (13:55–22:05) and night shift (21:55h–06:05) at fixed times, starting at 06:40 during morning shifts, at 14:40 during evening shifts and at 22:40 during night shifts; within each shift, participants were tested four times in 2-h intervals. The tasks were performed at the work place and monitored by researchers. All participants were tested on their third day within a given

Table 1. Absolute number of participants for type of shift and corresponding test order.

| Sample size | First tested shift | Second tested shift | Third tested shift |
|---|---|---|---|
| Morning shift | 11 | 4 | 19 |
| Evening shift | 13 | 17 | 4 |
| Night shift | 10 | 13 | 11 |

Table 2. Schematic representation of the shift system in study Site 1.

| Week | Sun | Mon | Tue | Wed | Thu | Fri | Sat |
|---|---|---|---|---|---|---|---|
| 1 | – | M | M | M[a] | M | M | M |
| 2 | – | E | E | N | N | N[a] | – |
| 3 | – | – | – | E | E | E[a] | E |
| 4 | N | N | N[a] | – | – | – | – |

Note: M = morning shift, E = evening shift, N = night shift.

[a] A possible test day. Free days are symbolised by a dash. Note that two test days were possible for the night shift. Yet, all participants were only tested once for each type of shift.

shift, i.e. on the third morning shift, third evening shift and third night shift. Thus, participants had time to adapt to the respective shift. Table 1 illustrates the distribution of participants as a function of the test order.

### 2.3 *Shift schedule*

The study was conducted at two factory sites in Berlin, Germany. At Site 1, the employees – all belonging to one hierarchical level – 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, special, customised motors, dynamos and generators were produced. The working steps, such as varnishing, assembling parts and welding, were comparable across sites. Site 1 had a forwards-rotating shift schedule (see Table 2).

For the purpose of our study, Site 2 changed to a forwards-directed shift schedule (i.e. five morning shifts, two free; five evening shifts, two free; five night shifts, two free) for the duration of the study. Normally, workers adhered to a self-chosen shift schedule, where the shifts covered by the participants could either be morning and evening shifts, or morning, evening and night shifts. Note that all participants also had to cover morning, evening and night shifts within their self-selected work times; thus, the main change concerned the regularity and the speed of rotation in study Site 2. Participants worked one block of evening shifts prior to the test sessions, aiming at minimising the acute negative effects of morning and night shifts on performance and sleep.

### 2.4 *Materials*

#### 2.4.1 *Assessment of handwriting kinematics*

We used personal digital assistant computers (PDAs, Hewlett Packard, HP iPAQ h × 2400 Family) to record handwriting movements. The PDAs are small (width 76.6 mm, depth 16.3 mm, height 119.4 mm) and lightweight (164.4 g). The touch screen (diagonal size: 89 mm; $x$-axis = 55 mm; $y$-axis = 72 mm) registers the position of the detachable stylus (size: 96 mm; diameter: 4 mm; weight: 1 g) and displays the written path until the end of each trial. Sampling frequency corresponds to 120 Hz with a spatial resolution of 0.24 mm (240 × 320 pixel).

Participants were instructed to (1) write the German word 'Wellen' (waves) three times in their normal style of handwriting and to (2) produce superimposed circles for 3 s (five times) in a fluent, quick way without lifting the pen (see Supplementary Material, Figure S1 and Table S1). Participants have been told to use their accustomed pen grip for the execution of the tasks. Please refer to Figures 1 and 2 for a demonstration of the task procedure.

Both tasks have been extensively used in handwriting studies to assess the writing of simple text ('Wellen' as part of a four-word test sentence) and the generation of basic script elements (superimposed circles) in healthy subjects and patients with neurological deficits (Marquardt, Gentz, and Mai 1996; Mergl et al. 1999; Zeuner et al. 2007; Jasper et al. 2009a, 2009b; Schneider et al. 2010).

The two-dimensional coordinates of the written paths, stored on the PDA, were transferred to a standard personal computer and the kinematics were analysed with specialised software (CS, MedCom, Munich, Germany). Data were

Figure 1. Hand-held device (PDA) and task execution (superimposed circles).

smoothed, and velocity as well as acceleration were calculated using a filter method (kernel estimation) optimised for kinematic analysis of handwriting (Marquardt and Mai 1994).

### 2.4.2 *Munich ChronoType Questionnaire (MCTQ$^{Shift}$)*

The MCTQ$^{\mathrm{Shift}}$ is a version of the Munich ChronoType Questionnaire (Roenneberg, Wirz-Justice, and Merrow 2003) that has been adapted for shift workers (Juda, Vetter, and Roenneberg 2013b). It assesses sleep/wake behaviour across shifts and their respective free days and thereby allows the computation of a sleep-phase derived phase of entrainment, or chronotype. In day workers, chronotype is assessed by mid-sleep on free days (mid-point between sleep onset and offset), corrected for sleep deficit accumulated during the workweek, MSF$_{\mathrm{sc}}$ (Roenneberg et al. 2012). In shift workers, chronotype is assessed most reliably by mid-sleep on free days after evening shifts, corrected for potential sleep debt (MSF$^{\mathrm{E}}_{\mathrm{sc}}$). The rationale behind this choice is that evening shifts least affect sleep/wake behaviour on free days, unlike morning and night shifts (Juda, Vetter, and Roenneberg 2013b). Yet, not all shift schedules comprise free days after evening shifts, as, for example, in our sample working in study Site 1. Therefore, Juda, Vetter, and Roenneberg (2013b) have proposed a correction algorithm allowing to determine the chronotype of shift workers on the basis of mid-sleep on free days after morning or night shifts. Out of the 34 participants, 29 completed the MCTQ$^{\mathrm{shift}}$. The participants' mean MSF$^{\mathrm{E}}_{\mathrm{sc}}$ was 04:38 (±01:16, range: 02:43–07:58). For participants in study Site 1 ($n = 21$), MSF$^{\mathrm{E}}_{\mathrm{sc}}$ was obtained by converting the mid-sleep on free days after night

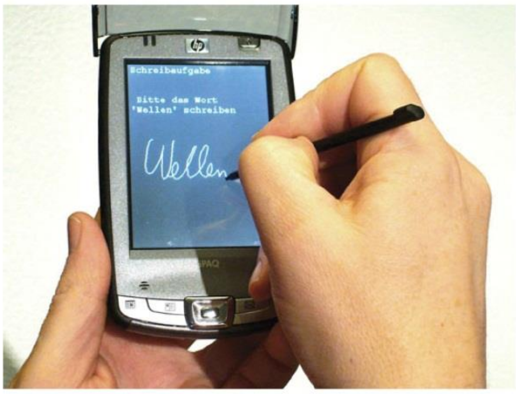

Figure 2. Hand-held device (PDA) and task execution (word 'Wellen').

shifts ($MSF_{sc}^{N}$) to $MSF_{sc}^{E}$, while study Site 2 ($n = 8$) comprised free days after evening shifts, resulting in direct assessment of $MSF_{sc}^{E}$.

### *2.4.3 Sleep logs*

Participants continuously filled out sleep logs during the study period, indicating their bedtime (BT), 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 wake-up time at a given test day (i.e. Sl_Off on a test day).

## ***2.5 Data analysis***

The analysis software CS segmented the written trace into subsequent up and down strokes (see Supplementary Material, Figure S1 and Table S1). Participants were instructed to write 'horizontally', e.g. orthogonally to the long axis of the display (*y*-axis). The resulting script samples did not yield appreciable tilts, so that no rotation was considered necessary. The segmentation algorithm searched for minima and maxima in the 'vertical' position signal (along the *y*-axis). An up-stroke was defined as a movement from minima to maxima and a down-stroke from maxima to minima. Following kinematic handwriting parameters were extracted for each trial.

Average velocity (mm/s): distance travelled by the stylus divided by writing duration.
Script size (mm): average script size in the vertical direction of the letters/circles.
Frequency (Hz): average number of up and down strokes per second ('Wellen' and circles).

All three dependent variables, i.e. velocity, script size and frequency, are expressed as deviation from individual mean (as derived from the 12 test points over the three testing days for each participant) to control for inter-individual variation in fine motor coordination. Prior to this normalisation procedure, mean velocity was 79.6 mm/s (± 26 mm) for the written word and 131.3 mm/s (± 60 mm) for the superimposed circles with an average frequency of 4.46 Hz (± 0.8 Hz) and 4.75 Hz (± 0.85 Hz), respectively. Mean script size for the word 'Wellen' corresponded to 7.7 mm (± 2.6 mm) and 10.6 mm (± 5.6 mm) for the superimposed circles.

Potential sequence or training effects were estimated by an analysis of variance (ANOVA) with the within-subject factors order (i.e. tested first, second or third) and session; to do so, we ranked the individual shifts according to their appearance. To analyse the effect of task complexity, we used a three-factorial ANOVA for repeated measures with shift (morning, evening, night), test session (sessions 1–4) and writing task (word: 'Wellen', circles) as within-subject factors. If task did not influence handwriting performance, data were averaged across the two conditions (circles and word 'Wellen'), followed by a two-factorial ANOVA with shift (morning, evening, night) and test session (session 1–4) as within-subject factors. Fisher-LSD post hoc tests for multiple, pairwise comparisons were conducted at a global two-sided level of significance of 0.05.

To assess whether there were significant differences between the 12 test points, we performed paired *t*-tests.

Script size and velocity usually correlate highly with one another (e.g. Wing 1978; Lacquaniti, Terzuolo, and Viviani 1983; Viviani and McCollum 1983; Rosenblum, Weiss, and Parush 2003). We explored whether this common result can be reproduced within the setting of our study and compared relative script size and velocity during the sessions of each shift (Pearson correlations, alpha levels corrected for multiple testing using Bonferroni correction).

We analysed the sleep parameters gathered with repeated measures ANOVAs with the within-factor shift. Fisher-LSD post hoc tests were used to examine differences between shifts. We explored shift-specific differences for time awake on a test day, as well as sleep duration before a test day. The latter was expressed as a proportion of average sleep duration before the three tested shifts to account for inter-individual differences in average sleep duration (Ursin, Bjorvatn, and Holsten 2005).

## **3. Results**

Figure 3 shows handwriting performance ($n = 34$) on a group level across morning, evening and night shifts.

## ***3.1 Effects of shift and session on handwriting velocity***

We did not detect an effect of testing sequence on writing velocity (ANOVA with the factor test order: $F < 1$, $p > 0.1$, session: $F < 1$, $p > 0.1$, interaction between shift and session $F < 1$, $p > 0.1$) indicating that performance was not influenced by the test order of the shifts.

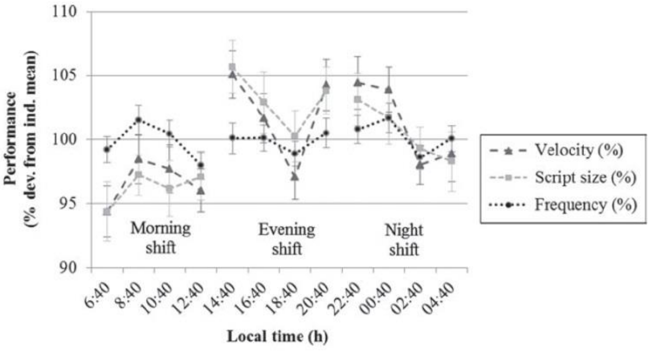

Figure 3. Average velocity, script size and frequency (all in % deviation from individual mean) across morning, evening and night shifts and all sessions, ±1 SEM.

The time course of relative handwriting velocity (see Figure 3) was independent of task complexity (ANOVA, interaction between task and shift $F < 1$, $p > 0.1$, interaction between task and session $F < 1$, $p > 0.1$). Consequently, data were averaged across tasks. The following ANOVA revealed a significant influence of shift ($F(2, 66) = 3.57$, $p < 0.05$) on writing velocity, with slower performances during morning and night shifts as compared to during evening shifts (Fisher-LSD post hoc tests: morning vs. evening shift: $p < 0.05$, mean difference: 5.4% ± 2.2%; morning vs. night shift $p \leq 0.05$, mean difference: 4.6% ± 2.3%, evening vs. night shift: $p > 0.05$, mean difference: 0.7% ± 2%). Average velocity was also influenced by test session (1–4) ($F(3, 99) = 2.94$, $p < 0.05$) and by the interaction between shift and session ($F(6, 198) = 3.86$, $p < 0.001$). Paired *t*-tests between successive sessions over the different shifts confirmed that velocity during the first test session of the morning shift was significantly slower than during the second one (06:40 vs. 08:40: $p < 0.05$), also the last session of the morning shift showed reduced writing speed with comparison to the first session of the evening shift (12:40 vs. 14:40: $p < 0.01$). Handwriting velocity increased between 18:40 and 20.40 ($p < 0.001$). Furthermore, night shift performance decreased significantly between the second and third session (0:40 vs. 2:40: $p < 0.01$).

Overall writing was slowest during the first session of the morning shift (6:40: 94.39% = −5.61%) and fastest during the first session of the evening shift (14:40: 105.8% = +5.8%), resulting in a maximum performance difference of ~11%.

### 3.2 *Effects of shift and session on script size*

As for velocity, no order effect could be detected (ANOVA with the factor test order: $F < 1$, $p > 0.1$, session: $F < 1$, $p > 0.1$, interaction between shift and session $F < 1$, $p > 0.1$).

Relative script size was independent of task complexity (ANOVA, interaction between task and shift, $F(2, 66) = 2.77$, $p > 0.05$; interaction between task and session, $F(3, 99) = 1.29$, $p > 0.1$). We therefore averaged the data across tasks, as described above for average velocity. Script size was smallest during morning shifts (main effect of shift, $F(2, 66) = 4.73$, $p < 0.01$), and differed significantly from evening and nights shifts (Fisher-LSD post hoc tests: morning vs. evening shift, $p < 0.01$; morning vs. night shift: $p < 0.05$; evening vs. night shift: $p > 0.1$). Neither test session ($F(3, 99) = 1.05$, $p > 0.1$) nor the interaction between session and shift reached significance ($F(6, 198) = 1.3$, $p > 0.1$). During the first session of the morning shift script size was smallest (−5.61%) and highest during the first session of the evening shift (+5.68%).

### 3.3 *Effects of shift and session on handwriting frequency*

As for velocity and script size, handwriting frequency was not influenced by task complexity (ANOVA, interaction between task and shift, interaction between task and session $F < 1$, $p > 0.1$) and we therefore averaged data across the two conditions. Average handwriting frequency showed an order effect (ANOVA factor shift order: $F(2, 66) = 4.250$, $p < 0.05$, session: $F(3, 99) = 2.31$, $p > 0.05$, interaction between session and shift order: $F(6, 198) = 1.76$, $p > 0.1$), with frequency increasing depending on the shift order and being fastest in the last shift that was performed. In the following ANOVA, regarding shift and session as main factors, no effects (shift: $F(2, 66) = 0.08$, $p > 0.1$; session: $F(3, 99) = 2.31$, $p > 0.05$; interaction between shift and session: $F(6, 198) = 1.9$, $p > 0.05$) have been found.

### 3.4 *Correlation between mean size and velocity*

There were strong positive correlations between mean size and velocity in all sessions of the respective shifts (Bonferroni corrected, all Pearson correlation coefficients $r \geq 0.69$, all $p \leq 0.001$, $n = 34$).

### 3.5 *Sleep variables*

An overview of sleep duration and time awake at the first test session is summarised in Table 3.

Shift significantly impacted on time awake ($F(2, 58) = 65.32$, $p < 0.001$), with time awake being shortest before morning shifts and longest before night shifts (Fisher-LSD post hoc tests all $p < 0.001$). Also, relative sleep duration showed an effect of shift ($F(2, 54) = 13.10$, $p < 0.05$) with shortest sleep duration before morning shifts, and longest before evening ones (Fisher-LSD post hoc tests between morning vs. evening shift: $p < 0.001$; evening vs. night shift: $p < 0.05$; morning vs. night shift: $p < 0.05$).

## 4. Discussion

To date, the profile of handwriting as an example of routine fine motor control across 24 h in a work environment has not been investigated. The present field study reports significant time of day effects on movement fluency and coordination of handwriting performance, i.e. mean velocity and script size, as assessed in shift workers. Worst performance levels were observed during morning shifts (minimum at 06:40), best performance during evening shifts (maximum at 14:40). The time courses for average velocity and script size were very similar, and as expected the two measures were strongly correlated (Wing 1978; Lacquaniti, Terzuolo, and Viviani1983; Viviani and McCollum 1983; Rosenblum, Weiss, and Parush 2003). Unlike in constant routine protocols, handwriting frequency showed large training effects. Task complexity did not influence fine motor performance. Drawing superimposed circles or writing a word did not have an impact on relative velocity, script size and frequency, at least in this real-world environment.

In previous studies an endogenous rhythm for human motor activity (Ivanov et al. 2007) and gross motor control (Jasper et al. 2009a) was described in laboratory constant routine conditions. Our study setting differed strongly from those controlled conditions, as we tested participants with a wide range of chronotypes, experiencing differential levels of sleep deprivation and sleep pressure due to increased time awake. Although it is likely that fine motor performance in our study is still under control of the endogenous rhythm, it is most likely masked by those external factors.

Investigations that assessed handwriting in constant routine settings under extended wakefulness over 40 h reported that handwriting frequency in particular and mean velocity showed an endogenous circadian rhythm (Jasper et al. 2009a, 2009b). In these studies handwriting frequency and velocity increased in the morning hours, remained stable during the afternoon and evening hours and started to decrease at 21:00 with a performance minimum at 03:00. With extended wakefulness, handwriting performance increased again and reached comparable performance levels by noon (i.e. up to 28 h later and under complete sleep deprivation). This consolidation of performance levels is interpreted as circadian compensation (Jasper et al. 2009a, 2009b). In the present study, which by its nature confounds the influence of the circadian and the homeostatic system, we observed differences in the time course of fine motor performance. We found a performance minimum in the early morning hours at 6:40, stable levels in the afternoon and evening and detected a decline starting at 00:40. The fact that we observed worst performance at the beginning of the morning shift appears counter-intuitive at first glance. However, former studies amongst shift workers showed that sleep duration before a test day is a decisive factor of performance (Ferguson et al. 2011; Vetter, Juda, and Roenneberg 2012; Juda, Vetter, and Roenneberg 2013a). In our study, sleep duration was shortest before morning shifts, and this is where we also observed worst performance.

Furthermore, most of the constant routine studies are conducted with participants of intermediate chronotype only, unless extreme early or late chronotypes are in the focus of a study. On average, our sample could be qualified as intermediate chronotypes ($\mathrm{MSF}^{\mathrm{E}}_{\mathrm{sc}}$ of 04:38 ± 01:16). Yet, since our chronotypes ranged from moderately early types ($\mathrm{MSF}^{\mathrm{E}}_{\mathrm{sc}}$ of 02:38) to very late ones ($\mathrm{MSF}^{\mathrm{E}}_{\mathrm{sc}}$ of 07:58), we have a considerably more heterogeneous sample as compared to

Table 3. Average sleep duration before the respective shift (% of individual mean and in hours) and time awake (h) at the first testing session of the shift.

| | Morning shift | Evening shift | Night shift |
|---|---|---|---|
| Sleep duration (%, ± SD) | 88.14 (± 11.89) | 113.21 (± 15.21) | 98.78 (± 14.97) |
| (in hours, ± SD) | 5.28 (± 1.04) | 6.8 (± 1.48) | 5.92 (± 1.27) |
| Time awake (in hours, ± SD) | 2.97 (± 2.51) | 6.23 (± 1.79) | 8.61 (± 1.8) |

laboratory studies. The differential time course of our study results could therefore partially be explained by this high variability of chronotypes in our sample.

Previous shift work studies have shown that older shift workers experience more mal-adaptation to shift work (Akerstedt and Torsvall 1981; Matsumoto and Morita 1987; Härmä et al. 1990) and reported reduced performance levels especially during night shift (Reid and Dawson 2001; Petrilli et al. 2005). As this study is based on a convenience sample, the age range was quite large (20–59 years), and the small sample size did not allow an age group-specific analysis. However, further systematic studies with larger groups are needed to elucidate the impact of age, chronotype and sleep on handwriting performance and shed light on the factors responsible for the discrepancy between our field study data and those obtained in laboratory settings.

In the present study, handwriting frequency was the only parameter influenced by testing order as reflected in a steady improvement in performance (see Results section) – even if testing was preceded by extensive training sessions. In constant routine protocols, handwriting frequency, however, was not susceptible to training effects (Jasper et al. 2009a, 2009b). This suggests that even parameters of highly automatised fine motor skills, such as handwriting, show differential training effects when tested repeatedly in a constant routine protocol as compared to repetitive testing across a three-week study period. A direct transfer from laboratory to field studies when examining learning and training procedures should therefore be considered with caution. Our finding also indicates that frequency may be suitable to evaluate the success of training procedures in handwriting, as has been reported before in patients with writer's cramp (Mai and Marquardt 1994; Hermsdörfer et al. 2011).

The fact that task complexity did not impact fine motor kinematics is in agreement with previous laboratory results (Jasper et al. 2009a, 2009b) showing differences in absolute performance indicators, but not with regard to their time course across the 24-h day.

In more recent studies (Jasper et al. 2009a, 2009b) it has been reported that script size was not influenced by time of day under constant conditions. This is in contrast with our observations. Yet, earlier studies by Glenville et al. (1987) reported that script size tended to be smaller after one night of sleep deprivation and that time of day had an impact with increased script size during the afternoon as compared to the morning hours. This parallels our present observations that script size was smallest during morning shift and largest during the evening shift.

In general, due to intense experience, handwriting is a highly automated, overlearned sensorimotor skill that is frequently performed in everyday life (van Galen 1990, 1991). It has also been reported that in healthy adults, handwriting movements represent automated movements which do not require conscious control and have no attentional requirements (Longstaff and Heath 1997; Tucha and Lange 2001). Participants were instructed to use their accustomed style of handwriting (explicitly 'calligraphy' was not demanded) and to circle quickly and fluently; thus, we assume the impact of visual acuity to be minimal. However, it cannot be fully excluded that motivational factors impacted on handwriting kinematics. Since the kinematical analysis evaluates objective measures of short units of performance (Rosenblum, Weiss, and Parush 2003), we do not assume that motivational factors significantly impacted on the results. A former study that investigated the time of day effects of a visuomotor tracking task did not find a correlation between alertness ratings and tracking performance (Petrilli et al. 2005), which supports our assumption.

However, it is clear that the testing device itself used to assess fine motor control differs from the ones used in previous laboratory-based studies. Rather than using a tablet PC, we implemented the tasks on portable pocket PCs, where handwriting was assessed by a stylus. We instructed and trained the participants before the experiment to use their accustomed pen grip (mostly the touch pen was grasped with the thumb, index and middle finger) and style of handwriting. Stylus size (length: 96 mm; diameter: 4 mm) was smaller compared to the dimensions of most available ballpoint pens, although typical in size for touch pens (Kao and Liang 2002). Former studies reported best handwriting and drawing performances (handwriting duration and accuracy) for pens with diameters of about 8 mm and lengths of 100 mm (Peck, Askov, and Fairchild 1980; Wu and Luo 2006; Goonetilleke, Hoffmann, and Luximon 2009); thus, our handwriting task was possibly more complex due to the reduced pen dimensions. Wu and Luo (2006) investigated hand stability during screen writing and drawing in a sitting position and reported that participants tend to use unnatural gestures such as local elbow, wrist and little finger support and unusual pen grips. We did not observe such variations in gestures or pen grip, but, nevertheless, it can be assumed that the standing position was unusual and less hand support was available. However, the variations we observe in typical kinematic handwriting parameters are comparable to those obtained with standard graphic tablets. We therefore assume that the unusual setting may have increased the complexity of the handwriting task, but did not substantially weaken its validity.

As fine motor skills are indispensable for accurate and effective production, our data are potentially of economic relevance. The variations across shifts are largely consistent between parameters and should be especially relevant for production processes that require steady and high levels of fine motor control. In addition, deficits of fine motor coordination may also be associated with accidents. Whereas most reports of work accidents contribute the highest risk to the night shift, an analysis of 3470 accidents amongst monthly rotating shift workers in the textile industry by Nag and Patel (1998) demonstrated that the first half of the morning shift in particular requires special attention for safety control, which is in line with our results. We suggest for future research to systematically investigate the relationship between fine motor control and production efficiency or accident rates. Ultimately, this may contribute to improved health and safety recommendations, especially in the context of tasks requiring steady and precise fine motor control.

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

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# 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

## 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

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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 shiftwork 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

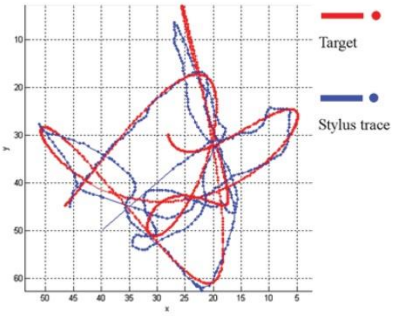

*Figure 1.* Exemplary graphical performance report of one 10-s trial of two-dimensional tracking: Illustrated are the target line (red line) and the participant's trace (blue line; *x*- and *y*-axes are depicted in mm).

*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:

$$y(t) = \sin(2\pi \cdot f1 \cdot t + \varphi 1) + \sin(2\pi \cdot 0.68 f1 \cdot t + \varphi 2) + \sin(2\pi \cdot 0.43 f1 \cdot t + \varphi 3)$$

$$x(t) = \sin(2\pi \cdot f2 \cdot t + \varphi 4) + \sin(2\pi \cdot 0.68 f2 \cdot t + \varphi 5) + \sin(2\pi \cdot 0.43 f2 \cdot t + \varphi 6)$$

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

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:

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

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

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

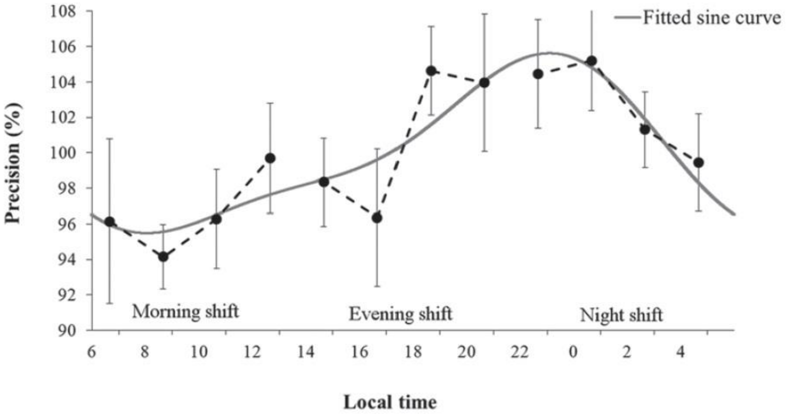

*Figure 3.* Precision (%) during the sessions of the shifts and a 24-hr fit with an additional 12-hr harmonic component (solid line). Bars indicate standard error (*SE*) of the mean (+/– *1 SE*).

(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.

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# 7. Eigenanteil an den vorgelegten Arbeiten

Die Doktorandin, die in beiden Publikationen als Erstautorin auftritt, hat die vorliegenden Daten mit einem Studienteam vor Ort erhoben und im Anschluss eigenständig ausgewertet. Die Vorbereitungen für die Studie erfolgten in Zusammenarbeit mit Prof. Dr. rer. biol. hum. Joachim Hermsdörfer, Dr. phil. Celine Vetter und dem Studienteam. Beide Veröffentlichungen wurden zunächst durch die Doktorandin selbst verfasst, im Anschluss in Zusammenarbeit mit Prof. Dr. rer. biol. hum. Joachim Hermsdörfer und Dr. phil. Celine Vetter überarbeitet und in die endgültige Form gebracht. Der Coautor Christian Tatarau stand als Programmierer der Aufgaben bei technischen Fragen für den Methodenteil unterstützend zur Seite.

# 8. Eidesstattliche Versicherung

Ich, Patricia Hölzle, erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Thema:

„Der Einfluss der Tageszeit auf die Schreib- und Trackingleistung bei Schichtarbeitern“

selbständig verfasst, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

Ich erkläre des Weiteren, dass die hier vorgelegte Dissertation nicht in gleicher oder in ähnlicher Form bei einer anderen Stelle zur Erlangung eines akademischen Grades eingereicht wurde.

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München, den 17.8.2014

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Unterschrift Doktorandin

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