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ORIGINAL INVESTIGATION

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Effects of nicotine chewing gum on a real-life motor task: a kinematic analysis of handwriting movements in smokers and non-smokers

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Abstract *Rationale:* In laboratory tasks nicotine has consistently been shown to improve psychomotor performance. *Objectives:* The aim of the present experiment was to assess the effects of nicotine on a skilled task of everyday life in smoking and non-smoking healthy adults. *Methods:* Assessment of handwriting movements of 38 non-deprived smokers and 38 non-smokers was performed following the chewing of gum containing 0 mg, 2 mg or 4 mg of nicotine. A digitising tablet was used for the assessment of fine motor movements. Subjects were asked to perform a simple writing task. Movement time, velocity and acceleration of the handwriting movements were measured. Furthermore, every writing specimen was independently rated by two examiners regarding the quality of handwriting. *Results:* Kinematic analysis of writing movements revealed that nicotine could produce absolute improvements in handwriting. Following nicotine administration, reduced movement times, increased velocities and more fluent handwriting movements were observed. These improvements were more striking in smokers than in non-smokers. No effects of nicotine were found with regard to the quality of handwriting. *Conclusion:* The results suggest that nicotine can enhance psychomotor performance to a significant degree in a real-life motor task.

Keywords Nicotine · Human · Handwriting · Movement analysis · Kinematic analysis

Introduction

Nicotine, the most psychoactive component of tobacco, is addictive and has been shown to produce various effects on the peripheral and central nervous system. Subjective reports of smokers indicate that people smoke both to reduce stress and to enhance cognitive performance, in particular attention (Kerr et al. 1991; LeHouezec et al. 1994; Kassel 1997; Levin et al. 1998; Warburton and Mancuso 1998; Mancuso et al. 1999; Waters and Sutton 2000). The reports of positive cognition-enhancing properties of nicotine are supported by a number of experimental studies in which varying aspects of cognition of non-deprived smokers, deprived smokers and non-smokers were assessed. These studies reported nicotine-induced improvements in a number of cognitive functions, including memory and attentional functions (Sherwood 1994; Kassel 1997; Heishman 1998). These positive effects appear to be absolute in nature indicating that nicotine effects true enhancement of performance rather than the relief of a withdrawal-induced deficit (Heishman 1998). However, it has to be emphasized that studies using laboratory tests including measures of cognitive and psychomotor functioning could not consistently demonstrate a nicotine-induced improvement of task performance in non-deprived smokers or non-smokers (Heishman 1998). Since the evidence concerning a true enhancement of cognitive functioning is still modest, further research is necessary. Following nicotine administration, improvements of cognitive functioning were also observed in patients with neuropsychiatric diseases such as Alzheimer's disease (White and Levin 1999), schizophrenia (LeHouezec 1998), Parkinson's disease (Fagerström et al. 1994), and adult attention deficit hyperactivity disorder (Levin et al. 1996; Rezvani and Levin 2001).

With regard to the effect of nicotine on motor functioning, there is little available data, although there is considerable evidence indicating that nicotine may influence motor performance. Clinical studies using nicotine skin patches and/or nicotine gum have also demonstrated the efficacy of nicotine in treating motor disturbances of patients with neuropsychiatric diseases. Following nicotine administration, severity and frequency of motor tics were significantly reduced in children with

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Tourette syndrome (Sanberg et al. 1997; Silver et al. 2001). Treatment with nicotine also resulted in improvements of motor functions in patients with Parkinson's disease (Ishikawa and Miyatake 1991; Fagerström et al. 1994; Clemens et al. 1995; Sanberg et al. 1997). Other studies, however, have found negative effects of nicotine on motor functions of patients with Parkinson's disease (Ebersbach et al. 1999). Furthermore, immediately after smoking, a transient deterioration of motor behaviour was observed in patients with multiple sclerosis (Emre and de Decker 1992). Experimental studies examining psychomotor functions in healthy subjects reported that finger tapping rate (Frith 1967; West and Jarvis 1986; Perkins et al. 1990, 1994, 1995; Heishman et al. 1994; Heishman 1998) and motor reaction time during tests of attention (Pritchard et al. 1992; LeHouezec et al. 1994) could be improved by nicotine. In addition, performance in a tracking task requiring motor activity in response to the processing of complex visual information has been found to be enhanced in non-deprived smokers and deprived smokers after nicotine administration (Hindmarch et al. 1990; Kerr et al. 1991).

Although nicotine has been shown to enhance psychomotor performance, the mechanisms by which this enhancement are effected remain uncertain. Nicotine acts as an agonist at nicotinic cholinergic receptors in the brain and peripheral nervous system. These receptors are widespread throughout the brain and are located presynaptically at cholinergic, dopaminergic and glutamatergic terminals. Stimulation of the nicotinic cholinergic receptors enhances the release of neurotransmitters at these nerve endings. High densities of central nicotinic cholinergic receptors have been found in various areas which are involved in movement control such as the midbrain tegmentum, subcortical forebrain nuclei including the striatum and nucleus accumbens, the substantia nigra pars compacta, the ventral tegmental area and cortical areas including the medial prefrontal cortex (Clarke and Pert 1985; Ghez 1991; London et al. 1996; Feldman et al. 1997; Pich et al. 1997). Furthermore, nicotinic cholinergic receptors have been identified in all striated muscles (Feldman et al. 1997).

The value of previous studies measuring the effects of nicotine on motor behaviour of healthy subjects appears to be limited by the fact that only simple motor tasks such as finger tapping or laboratory measures were performed. There is no available data concerning the effect of nicotine on motor functions involved in more complex and more familiar or even automated motor tasks. In the present study, kinematic aspects of handwriting movements of non-deprived smokers and non-smokers were analysed after the chewing of gum containing 0 mg, 2 mg and 4 mg nicotine. Handwriting is a highly skilled, coordinated motor activity. In previous research, handwriting movements have frequently been shown to be a sensitive measure of the effects of pharmacological agents (Tucha and Lange 2001; Tucha et al. 2002). High densities of nicotinic cholinergic receptors have been identified in areas related to the control and execution of movements and the speed component of tasks measuring psychomotor functioning such as tapping speed (West and Jarvis 1986) or motor reaction time (LeHouezec et al. 1994; Houlihan et al. 1996) appear to be sensitive to nicotine-induced improvements. We therefore predicted that nicotine administration will result in a faster movement execution as indicated by a reduced movement time and an increased writing velocity and fluency. Since adults usually produce automated handwriting movements, we expected no effect of nicotine administration on measures of handwriting quality such as legibility or accuracy.

Materials and methods

Subjects

Thirty-eight healthy habitual smokers (19 female 19 male; mean age=23.5 years; SEM=0.5 years) and 38 non-smokers (19 female 19 male; mean age=23.7 years; SEM=0.5 years) volunteered to take part in the experiment. In order to keep the sample of smokers as homogenous as possible, only those who classified themselves as inhalers were included in the study (Wesnes and Warburton 1983). All smokers smoked at least 15 cigarettes per day and had been smoking for a minimum of 5 years. The non-smoking subjects were required never to have been smokers (fewer than 5 cigarettes in lifetime). All subjects were students of the University of Regensburg and unfamiliar with nicotine gum. Subjects using prescription drugs or those who met any of the contraindicated conditions for nicotine use such as pregnancy, breast-feeding or a history of cardiovascular disease were not included in the experiment. Furthermore, all subjects entering the experiment met the following criteria: age between 20 and 35 years, right-handedness, no history of neurological or psychiatric disease, no history of skeletomotor or sensorimotor dysfunction and no history of drug or alcohol abuse. The study was approved by the ethics committee of the University of Regensburg and has therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Prior to participating in the experiment all subjects gave written informed consent. Subjects were aware that involvement in the study was voluntary and that they could withdraw from the experiment at any time. All subjects were informed of the nature of the experiment and that they would receive nicotine and a placebo during the course of the experiment. Subjects were required not to consume alcohol, tea, coffee or other caffeine or alcohol containing products overnight. The smokers were not asked to abstain from smoking before the experiment, so that all subjects were at their usual nicotine levels.

Design and medication

Handwriting movements of each subject were assessed under three different conditions of nicotine administration. The conditions consisted of a placebo (0 mg nicotine) and two nicotine conditions (2 mg or 4 mg nicotine). The order of administration was based on a random allocation sequence formulated by an investigator not participating in the execution of the experiment. Nicotine was administered orally as a 0 mg, 2 mg or 4 mg nicotine polacrilex gum (Nicorette gum). To disguise the presence of nicotine, a drop of red pepper sauce was added to all pieces of gum. Administration of nicotine gum or placebo was performed double blind. According to Feldman et al. (1997) chewing a 2 mg nicotine gum results in a plasma nicotine concentration of approximately 11.8 μg/l, while chewing a 4 mg gum produces a concentration of about 23.2 μg/l.

Procedure

All subjects were tested individually in three sessions on alternate days. Assessment of handwriting movements was performed in the morning of each test day. While smokers were permitted to smoke freely until the start of a session, they were required to abstain from smoking until the assessment was completed for that session. The chewing gum was given at the start of each session. After receiving chewing gum, subjects were asked to chew the gum slowly and steadily for 20 min. During this 20-min period the subjects completed questionnaires. The results of these questionnaires were not considered in the present study. Handwriting movement samples were recorded in a laboratory room with constant temperature, noise and illumination levels, using a digitising tablet (WACOM IV, Germany) with a special pen containing a normal ink refill. The position of the pen on the tablet, velocity and acceleration were measured continuously during writing. The digitising tablet used in this study had a maximum sampling rate of 200 Hz. Data was stored on a personal computer that was connected to the tablet. The tip of the pen could be localised with an accuracy of 0.2 mm. Furthermore, movements of the pen tip above the paper, up to a maximum of 1.3 cm, could also be recorded. Data processing was performed with a computational program for the analysis of handwriting movements (Mai and Marquardt 1992). Kinematic data were calculated and smoothed using nonparametric regression methods (nonparametric kernel estimation) devised by Marquardt and Mai (1994). The subjects were asked to write the sentence "Ein helles grelles Licht" (a bright and glaring light). This task was repeated four times so that the sentence was written a total of 5 times by each subject. Before the start of these writing tasks, several practice trials were undertaken in order to familiarize the subjects with the writing tablet. The tablet was constructed to resemble a common desk pad in order that subjects could produce their usual handwriting. No restrictions of posture, speed or size of writing were imposed. During writing the subjects received a natural visual feedback on hand movements.

Analysis of handwriting

For data analysis, the total writing time (movement time) and the distance of the writing trace of the test sentence were recorded per trial. Movement time (in ms) was defined as the time between the first and final movement of the writing of the test sentence. The distance of the writing trace (in mm) was operationalised as the distance covered by the pen during the writing of the test sentence. Furthermore, the letter combination "ll" of the German words "helles" (bright) and "grelles" (glaring) were taken for the assessment of kinematic aspects of handwriting. Kinematic analysis of the letter combination "ll" was performed, since the examination of the dynamic and static writing trace may often require its segmentation into meaningful units. From a motor viewpoint, single letters and in particular single strokes are the smallest relevant units of the handwriting movement. The letter combination "ll" was chosen since these letters represent a simple letter combination that is usually executed in script type. Furthermore, while writing the letter combination "ll", the pen remains in contact with the tablet. In the evaluation of kinematic data, the maximum and minimum absolute (tangential) velocities and both the maximum positive and negative absolute acceleration (slowing down) of ascending and descending strokes were measured. In addition, the number of inversions of the direction of the absolute velocity (NIV) and acceleration profiles (NIA) of the letter combination "ll" were calculated. Kinematic analysis was performed for each sentence. For further analysis, mean scores were calculated for each subject as a measure of motor performance for the various conditions. The NIV is a measure of the degree of movement automatisation. More fluent handwriting movements are reflected in a smaller number of inversions in velocity (Tucha et al. 2001). The motion parameters (e.g. number of inversions, maximum velocities) were chosen, since these parameters have been shown to be sensitive measures of alterations in handwriting movements (Eichhorn et al. 1996; Oliveira et al. 1997; Slavin et al. 1999; Tucha et al. 2000). Although these measures are not independent from one another, varying measures such as movement time, maximum velocity or NIV provide information on different aspects of movement execution. For example, while the NIV represent a measure of movement automatisation, movement time represents a measure of difficulty of single strokes or series of strokes (Teulings et al. 1997). The maximum velocity reflects the maximum speed of movement in the ascending or descending direction. The distinction between descending and ascending strokes appears to be necessary because experiments on healthy subjects regarding the writing slant or the constancy of handwriting revealed that ascending and descending strokes behave differently under varying spatial conditions (Maarse and Thomassen 1983; Thomassen and Teulings 1983). This difference is related to the dynamic properties of fingers, hand, wrist and arm movements during handwriting. The direction of handwriting is from left to right. The direction of down strokes therefore represents a primary direction, which corresponds with the isolated flexion of fingers (Dooijes 1983). In contrast to ascending strokes, no other joints are involved in the execution of descending strokes. Furthermore, while down strokes normally constitute parts of letters, up strokes constitute nearly all the connecting strokes between letters (Thomassen and Teulings 1983).

Furthermore, every writing specimen was rated independently by two examiners in regard to form, alignment, spacing, legibility and uniformity of handwriting. Judgements were made using 5-point scales ranging from 1=excellent to 5=poor. Raters underwent an extensive and systematic training regarding the evaluation of the quality of handwriting specimens. In this training, adult handwriting specimens were used which had been assessed by teachers experienced in the evaluation of handwriting. With the help of these handwriting specimens, important attributes of each aspect of quality were demonstrated to the raters (e.g. spacing: poor spacing within a word, poor spacing between words, poor spacing between lines, etc.). In the present study, examiners were not informed of the aim and design of the study. For statistical analysis, judgements of the examiners were averaged. The inter-rater reliability was high (Intraclass correlation between 0.83 and 0.94).

Data analysis

Statistical analysis was performed using Mann-Whitney *U*-tests, Friedman and Wilcoxon tests. Non-parametric tests were chosen since parametric tests require normally distributed data. This requirement is not fulfilled regarding the number of inversions in velocity and acceleration profiles. For statistical analysis an alpha level of 0.05 was applied. Furthermore, effect sizes for group differences and effect sizes for differences between paired observations were computed (Cohen 1988).

Results

Comparison between smokers and non-smokers

Comparison between groups over the three conditions of nicotine administration (placebo, 2 mg or 4 mg nicotine) using Mann-Whitney *U*-tests revealed no significant differences ($P>0.05$) with regard to handwriting quality (Table 1) and all motion parameters (Table 2). In addition, the analysis of effect sizes revealed negligible effects between groups ($d<0.2$) with the exception of small effects ($d>0.2$) concerning both the minimum velocity of ascending strokes in the placebo condition and NIV following 2 mg nicotine administration (effect sizes are not presented).

Table 1 Handwriting quality (means±SEM)

Variable	Placebo	Non-smokers			Smokers	
		2 mg nicotine gum	4 mg nicotine gum	Placebo	2 mg nicotine gum	4 mg nicotine gum
Spacing[a]	2.95±0.15	2.97±0.15	2.96±0.15	2.92±0.19	2.95±0.19	2.93±0.17
Form[a]	3.03±0.14	3.04±0.15	3.07±0.13	3.04±0.16	3.05±0.16	3.05±0.15
Alignment[a]	2.68±0.18	2.67±0.18	2.70±0.16	2.64±0.17	2.63±0.17	2.72±0.18
Uniformity[a]	2.96±0.13	2.92±0.13	2.93±0.17	2.92±0.14	2.93±0.15	2.91±0.16
Legibility[a]	2.57±0.17	2.58±0.18	2.55±0.17	2.59±0.18	2.61±0.19	2.57±0.18

[a] Judgements ranging from 1=excellent to 5=poor

Table 2 Kinematics of handwriting movements (means±SEM)

Variable	Placebo	Non-smokers			Smokers	
		2 mg nicotine gum	4 mg nicotine gum	Placebo	2 mg nicotine gum	4 mg nicotine gum
Movement time (in ms)	7677.1±239.2	7618.4±235.3	7379.5±200.9	8092.2±226.3	7749.9±203.2**	7494.0±219.3**
Distance of the writing trace (in mm)	394.1±15.5	406.9±16.2	408.3±15.8	406.8±15.6	408.9±16.5	407.2±16.9
Analysis of ascending strokes						
Maximum velocity (in mm/s)	102.7±5.4	106.6±5.5	113.0±5.8*	105.9±5.0	110.5±5.3	114.1±4.7**
Minimum velocity (in mm/s)	18.8±1.0	19.7±1.1	20.0±1.1	18.0±1.7	19.2±1.6*	20.3±1.8**
Maximum positive acceleration (in mm/s^2)	1582.6±111.6	1598.7±119.1	1669.5±110.9	1708.7±100.0	1709.7±100.6	1783.7±92.4
Maximum negative acceleration (in mm/s^2)	−2056.4±135.6	−2105.0±143.1	−2192.9±136.0	−2079.1±127.0	−2213.9±105.5	−2248.6±118.0
Analysis of descending strokes						
Maximum velocity (in mm/s)	96.6±5.0	99.6±5.8	105.5±5.7*	97.4±4.5	101.3±5.0*	102.1±4.2*
Minimum velocity (in mm/s)	35.0±1.8	35.6±2.3	36.0±2.0	32.1±2.0	34.8±2.0*	37.3±2.3*
Maximum positive acceleration (in mm/s^2)	1947.8±111.4	2085.8±139.1	2092.9±124.6	1943.2±103.7	2031.0±116.5	2031.9±88.5
Maximum negative acceleration (in mm/s^2)	−1554.6±109.8	−1673.1±135.0	−1677.2±121.2	−1624.0±91.6	−1660.8±110.4	−1667.8±97.0
Number of inversions in velocity (NIV)	9.3±0.3	9.0±0.3	8.6±0.3*	9.0±0.3	8.6±0.2	8.3±0.1**
Number of inversions in acceleration (NIA)	9.5±0.4	9.4±0.3	9.3±0.4	9.2±0.3	9.0±0.2	8.9±0.2

* $P \leq 0.05$ compared with the placebo condition (Wilcoxon test); ** $P \leq 0.01$ compared with the placebo condition (Wilcoxon test)

Handwriting quality

The comparison between conditions using Friedman tests revealed no significant differences with regard to handwriting quality in either smokers (spacing: χ^2=0.25; *df*=2; *P*=0.885/form: χ^2=0.08; *df*=2; *P*=0.960/alignment: χ^2=0.14; *df*=2; *P*=0.932/uniformity: χ^2=0.07; *df*=2; *P*=0.964/legibility: χ^2=0.17; *df*=2; *P*=0.918) or non-smokers (spacing: χ^2=0.02; *df*=2; *P*=0.990/form: χ^2=1.21; *df*=2; *P*=0.546/alignment: χ^2=4.76; *df*=2; *P*=0.788/uniformity: χ^2=0.08; *df*=2; *P*=0.959/legibility: χ^2=0.20; *df*=2; *P*=0.906). In addition, the analysis of effect sizes showed only negligible effects with the exception of a small effect concerning the alignment of handwriting between the 2 mg and 4 mg conditions (Table 3).

Movement time and distance of the writing trace

Non-smokers

The examination of movement distance and movement time using the Friedman test revealed no significant differences between the three conditions (movement distance: χ^2=2.53; *df*=2; *P*=0.283/movement time: χ^2=0.474; *df*=2; *P*=0.789). The analysis of effect sizes showed small to negligible effects (Table 4), indicating shorter movement times but longer movement distances with increasing doses of nicotine administration.

Table 3 Effect sizes for differences between paired observations concerning handwriting quality

Variable	Placebo vs 2 mg nicotine gum	Non-smokers			Smokers	
		Placebo vs 4 mg nicotine gum	2 mg nicotine gum vs 4 mg nicotine gum	Placebo vs 2 mg nicotine gum	Placebo vs 4 mg nicotine gum	2 mg nicotine gum vs 4 mg nicotine gum
Spacing	0.04	0.02	0.02	0.07	0.02	0.04
Form	0.03	0.09	0.07	0.02	0.02	0.00
Alignment	0.02	0.06	0.09	0.03	0.19	0.23
Uniformity	0.08	0.07	0.02	0.02	0.02	0.06
Legibility	0.03	0.05	0.09	0.06	0.05	0.15

Table 4 Effect sizes for differences between paired observations concerning kinematics of handwriting movements

Variable	Placebo vs 2 mg nicotine gum	Non-smokers			Smokers	
		Placebo vs 4 mg nicotine gum	2 mg nicotine gum vs 4 mg nicotine gum	Placebo vs 2 mg nicotine gum	Placebo vs 4 mg nicotine gum	2 mg nicotine gum vs 4 mg nicotine gum
Movement time (in ms)	0.09	0.32	0.30	0.61	0.75	0.37
Distance of the writing trace (in mm)	0.25	0.29	0.05	0.05	<0.01	0.04
Analysis of ascending strokes						
Maximum velocity (in mm/s)	0.25	0.53	0.38	0.28	0.48	0.27
Minimum velocity (in mm/s)	0.31	0.32	0.09	0.25	0.43	0.30
Maximum positive acceleration (in mm/s^2)	0.04	0.20	0.21	<0.01	0.19	0.25
Maximum negative acceleration (in mm/s^2)	0.12	0.28	0.22	0.30	0.35	0.12
Analysis of descending strokes						
Maximum velocity (in mm/s)	0.18	0.51	0.40	0.34	0.32	0.07
Minimum velocity (in mm/s)	0.10	0.12	0.06	0.51	0.63	0.34
Maximum positive acceleration (in mm/s^2)	0.26	0.26	0.02	0.27	0.21	<0.01
Maximum negative acceleration (in mm/s^2)	0.25	0.24	0.01	0.12	0.14	0.03
Number of inversions in velocity (NIV)	0.27	0.36	0.17	0.35	0.52	0.25
Number of inversions in acceleration (NIA)	0.09	0.17	0.11	0.17	0.24	0.13

Smokers

Statistical comparison between conditions (Friedman test) showed no significant differences with regard to movement distance (χ^2=1.79; *df*=2; *P*=0.410). However, a significant difference between conditions was observed with regard to movement time (χ^2=13.45; *df*=2; *P*=0.001). Subsequent post hoc analysis using the Wilcoxon test indicated that smokers displayed shorter movement times during the 2 mg and the 4 mg conditions when compared to the placebo condition (2 mg condition: *P*=0.002/4 mg condition: *P*=0.001). The comparison of movement times between the 2 mg and the 4 mg condition showed no significant difference (*P*=0.118). The analysis of effect sizes concerning movement distance revealed negligible effects between conditions (*d*<0.2). Medium effect sizes for movement time were observed between the placebo condition and both the 2 mg and the 4 mg condition (*d*>0.5). The effect size between the 2 mg and the 4 mg condition was small, indicating a shorter movement time under the 4 mg condition.

Ascending and descending strokes

Non-smokers

While no differences were observed between the three conditions of nicotine administration with regard to the minimum velocities (ascending strokes: χ^2=4.90; *df*=2; *P*=0.087/descending strokes: χ^2=1.47; *df*=2; *P*=0.479), the maximum positive accelerations (ascending strokes: χ^2=3.21; *df*=2; *P*=0.201/descending strokes: χ^2=1.47; *df*=2; *P*=0.479) and the maximum negative accelerations (ascending strokes: χ^2=1.32; *df*=2; *P*=0.518/descending strokes: χ^2=3.37; *df*=2; *P*=0.186), a significant difference was found in the maximum velocities of both ascending and descending strokes (ascending strokes: χ^2=7.00; *df*=2;

P=0.030/descending strokes: χ^2=7.58; df=2; P=0.023). Subsequent post hoc analysis revealed that, in comparison to the placebo condition, the administration of a 4 mg nicotine gum led to a significant increase in the maximum velocities (ascending strokes: P=0.016/descending strokes: P=0.042). No significant differences of maximum velocity were found between the placebo condition and the 2 mg condition (ascending strokes: P=0.100/descending strokes: P=0.249) or between the 2 mg and 4 mg condition (ascending strokes: P=0.237/descending strokes: P=0.094). While the differences concerning the maximum velocities represent medium effects (d>0.5), the remaining effect sizes were mostly small or negligible. The effect sizes pointed to an increase in velocity and acceleration with increasing doses of nicotine administration.

Smokers

While the maximum positive accelerations (ascending strokes: χ^2=4.49; df=2; P=0.106/descending strokes: χ^2=0.81; df=2; P=0.666) and the maximum negative accelerations (ascending strokes: χ^2=4.36; df=2; P=0.113/descending strokes: χ^2=1.61; df=2; P=0.446) of both ascending and descending strokes did not differ significantly between the three conditions of nicotine administration, significant differences were observed in the maximum velocities (ascending strokes: χ^2=10.49; df=2; P=0.005/descending strokes: χ^2=9.37; df=2; P=0.009) and minimum velocities (ascending strokes: χ^2=10.97; df=2; P=0.004/descending strokes: χ^2=6.29; df=2; P=0.043). Post hoc analysis showed that the maximum velocities (ascending strokes: P=0.010/descending strokes: P=0.011) and the minimum velocities (ascending strokes: P=0.003/descending strokes: P=0.026) of both the ascending and descending strokes were significantly faster in the 4 mg condition when compared to the placebo condition. Furthermore, the maximum velocity of the descending stroke (P=0.041) and the minimum velocities of both the ascending and descending strokes (ascending strokes: P=0.015/descending strokes: P=0.022) were significantly faster under the 2 mg condition than under the placebo condition. No significant differences were observed between the 2 mg and the 4 mg condition with regard to the velocity during the production of ascending and descending strokes (P>0.05). Furthermore, the difference between the placebo condition and the 2 mg condition concerning the maximum velocity of ascending strokes was not statistically significant (P=0.099). The majority of differences found between the nicotine conditions in the maximum and minimum velocities represent small to medium effects. The remaining differences were of small or negligible size. The effect sizes indicate an increase in velocity and acceleration with increasing doses of nicotine administration.

Number of inversions in velocity (NIV) and acceleration (NIA) profiles

Non-smokers

Significant differences between conditions were observed in NIV (χ^2=6.26; df=2; P=0.044) but not in NIA (χ^2=2.22; df=2; P=0.330). Further analysis (Wilcoxon test) of NIV revealed a significant decrease in the 4 mg condition when compared to the placebo condition (P=0.033). No significant differences were observed between the placebo condition and the 2 mg condition (P=0.072) or between the 2 mg and 4 mg condition (P=0.061). The effect sizes for differences between the placebo condition and both the 2 mg and the 4 mg condition in NIV were small (d>0.2) while the remaining effect sizes were negligible (d<0.2).

Smokers

Statistical analysis revealed a significant difference between nicotine conditions in NIV (χ^2=7.39; df=2; P=0.025). The examination of NIA did not reach significance (χ^2=0.14; df=2; P=0.993). Post hoc analysis indicated that NIV is significantly smaller under the 4 mg condition than under the placebo condition (P=0.003). The differences between the placebo condition and the 2 mg condition (P=0.279) and between the 2 mg and 4 mg condition (P=0.061) were not significant. While the effect size for the difference between the placebo condition and the 4 mg condition in NIV was medium, the remaining effects were small to negligible.

Discussion

Psychomotor performance of healthy smokers and non-smokers, including finger tapping, motor reaction time and tracking, has been shown to improve in both smokers and non-smokers following nicotine administration (West and Jarvis 1986; Hindmarch et al. 1990; Kerr et al. 1991; Sherwood 1993; Heishman et al. 1994). The present study has demonstrated that nicotine can also produce absolute improvements in handwriting movements, i.e. reduced movement times, increased velocities and more fluent movements. No effects of nicotine were observed with regard to handwriting quality. This finding contradicts a speed-accuracy trade-off that in general indicates that an increasing speed of movement execution is associated with a decline in accuracy and vice versa. Although the improvements were more striking in smokers than in non-smokers, the present findings confirm the previous literature. Furthermore, the present results showed that the stimulant action of nicotine on psychomotor performance is not only restricted to laboratory measures but may also apply to skilled tasks of everyday life such as handwriting. The present results support the assumption that smoking behaviour may be reinforced by the

beneficial effects of nicotine upon mental and psychomotor efficiency (Wesnes and Warburton 1983; Warburton 1989; Provost and Woodward 1991; Ghatan et al. 1998).

Examination of handwriting using a digitising tablet was performed since kinematic analysis of motion parameters allows the measurement of both improvement and deterioration of performance. In addition, these parameters have been shown to be sensitive to pharmacological treatment. Handwriting is a very complex psychomotor ability that constitutes a dynamic interplay of several motor subsystems including the arm-elbow system, the wrist system and the finger system (Thomassen and Teulings 1983). Nevertheless, in healthy adults handwriting is a well-habituated motor skill consisting of automated movements (Tucha et al. 2001). Pre-experimental training for the task, as suggested by Wesnes and Warburton (1983), was not necessary, since it would not lead to a higher level of skilled performance in the task during the experiment. Automated processes do not require conscious control and have no attentional requirements (Näätänen 1992). This appears to be an important factor in the present results since a variety of previous studies have demonstrated that there is a large attentional component in the effect of nicotine on the brain. Nevertheless, nicotine may not necessarily influence handwriting movements directly, since the effect could be mediated by effects on other dimensions such as mood or arousal (Waters and Sutton 2000). However, we assume that any influence of mood on handwriting performance could be excluded since nicotine-induced improvements were also found in non-smoking subjects. A number of these subjects complained of slight feelings of nausea during the nicotine conditions. In view of this, if there were a mediating effect of mood on handwriting, one would expect a deterioration of handwriting performance. An effect of arousal on handwriting movements also appears unlikely since automated motor processes (e.g. grasping of objects or walking) can be performed effectively even in early stages of fatigue. A number of studies suggest that motor performance measures are not adversely affected by at least commonly experienced levels of sleep deprivation (Martin and Gaddis 1981; Webb et al. 1981). As has been discussed in regard to a nicotine-induced decrease of the Stroop effect (Wesnes and Warburton 1983; Provost and Woodward 1991), one may assume that the improvements of handwriting movements following nicotine administration could be due to altered access to or processing of semantic information. However, the finding of a post hoc inspection of handwriting specimen, revealing that there were neither spelling errors nor illegible scribbles across conditions, makes this possibility unlikely.

With regard to effect sizes, the nicotine-induced improvements were mostly small. However, one should consider that skilled handwriting represents a highly automated process so that improvements are not easy to achieve. Therefore, even small effect sizes provide strong support for the beneficial effects of nicotine. The comparison of the effect sizes between the placebo condition and both nicotine conditions points to a dose-response relationship. Furthermore, the small effect sizes for differences between the two nicotine conditions (2 mg and 4 mg) also indicates dose-related effects, even though these differences did not reach significant levels. Higher doses of nicotine led to decreasing movement times, increasing velocities and an increasing fluency.

In conclusion, the present experiment reveals that nicotine can enhance psychomotor performance to a significant degree in a real-life motor task. This enhancement was observed in both non-deprived smokers and non-smokers and therefore appears to be absolute in nature. Furthermore, the present study has demonstrated that kinematic analysis of movements may contribute important information to the effects of nicotine. The aim of future studies could be to examine the impact of nicotine on further aspects of motor behaviour by performing kinematic analysis of three-dimensional movements.

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