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ORIGINAL INVESTIGATION

Long-term effects of cannabis on eye movement control in reading

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Abstract
Introduction Cannabis is known to produce substantial acute effects on human cognition and visuomotor skills. Many recent studies additionally revealed rather long-lasting effects on basic oculomotor control, especially after chronic use. However, it is still unknown to what extent these deficits play a role in everyday tasks that strongly rely on an efficient saccade system, such as reading.
Materials and methods In the present study, eye movements during sentence reading of 20 healthy long-term cannabis users (without acute tetrahydrocannabinol-intoxication) and 20 control participants were compared. Analyses focused on both spatial and temporal parameters of oculomotor control during reading.
Results Long-term cannabis users exhibited increased fixation durations, more revisiting of previously inspected text, and a substantial prolongation of word viewing times, which were highly inflated for longer and less frequent words.
Discussion The results indicate that relatively subtle performance deficits on the level of basic oculomotor control scale up as task complexity and cognitive demands increase.

Keywords Cannabis · THC · Reading · Adverse effects · Eye movements · Saccades · Long-term oculomotor effects

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Introduction

Cannabis is a commonly used drug that produces acute effects on perception, cognition, and behavior (see Solowij 1998) through its interaction with an endogenous cannabinoid receptor system (CN-1) that is widely distributed across the central nervous system (CNS; Herkenham et al. 1990; Glass et al. 1997). Recent research indicated that chronic cannabis use may also result in long-term effects, usually defined as persisting effects after at least 1 day of abstinence (Pope et al. 1995). Several well-designed studies (see Gonzalez et al. 2002 for corresponding design criteria) consistently revealed two major sources of cognitive long-term impairment, namely, a decrease of attention-related functions (e.g., Fletcher et al. 1996; Pope and Yurgelun-Todd 1996; Croft et al. 2001) and reduced memory performance (Fletcher et al. 1996; Rodgers 2000; Solowij and Battisti 2008; Solowij et al. 2002; Lamers et al. 2006). In the present study, we report evidence for long-term effects of chronic cannabis use on oculomotor control processes in reading.

Efficient oculomotor control is a prerequisite for a vast array of vital everyday tasks like navigation in traffic (e.g., Huestegge et al. 2010), reading (Huestegge et al. 2009b; Radach and Kennedy 2004; Rayner 1998), and visual search (e.g., Huestegge et al. 2002). Previous research on the effects of cannabis on eye movement control revealed both acute and long-term effects. For example, acute effects of cannabis were studied in a pre-post design involving the execution of basic visually and memory-guided eye movements in non-regular users (Ploner et al. 2002). As one key result, saccade latencies of visually guided saccades were increased (12 ms), and amplitudes of memory-guided saccades were greater 2 h after oral drug intake compared to baseline testing. However, the effects were rather small, and it remained unclear whether such subtle deficits might persist for longer periods of time (especially in chronic users) and whether they are meaningful in the context of everyday tasks.

A recent study in our lab (Huestegge et al. 2009a) compared performance of chronic users without acute intoxication and of control participants in a series of oculomotor paradigms, similar to the work on acute effects by Ploner et al. (2002, see above). In harmony with their work, we also found increased latencies of visually guided saccades (related to an impairment of the programming phase of saccades) and for increased saccade amplitudes to memorized saccade locations (related to an impairment of visual working memory).

Further studies suggested that these rather subtle deficits in oculomotor control may scale up as task complexity increases. In a study by Ehrenreich et al. (1999), 99 long-term users were tested with various neuropsychological assessments. Long-term users without acute intoxication exhibited prolonged response times in a visual scanning task, but not in other attention-related tasks, including divided attention, short-term memory, and alertness. The critical scanning task required efficient overt visual search for a target within a rectangular array of distractors. Interestingly, slowed responses were only found in users with a rather early age of consumption onset (<17; see also Stiglick and Kalant 1985; Soderstrom and Johnson 2003, for age of onset effects in animal studies).

In a follow-up study, we replicated the finding of slowed visual search with a new sample of participants (Huestegge et al. 2002) while monitoring participants' eye movements. The oculomotor data revealed increased saccade amplitudes (similar to the alteration of amplitudes in the basic oculomotor tasks), a higher rate of reinspections of previously fixated locations (probably associated with visual working memory deficits), and a more thorough search strategy in chronic users, the latter probably reflecting compensation processes as a response to the perceived visuomotor deficits. Taken together, these results indicated that chronic users exhibit substantial deficits in complex tasks that require efficient oculomotor control.

In the present study, we address the question whether chronic users are long-term impaired with respect to one of the most fundamental cognitive abilities in our society, reading for comprehension. Reading provides an excellent arena to examine how various levels and modules of processing act together to orchestrate a complex cognitive skill. Progress in this area has been quite substantial over the last three decades, resulting in a solid base for application in research on drug-induced performance deficits (see Kennedy et al. 2000; Radach et al. 2004, for recent overviews). Efficient visuomotor processing is a prerequisite of skilled reading (Findlay and Walker 1999; Rayner 1998), and if deficits of oculomotor control indeed scale up as task complexity increases, this should be reflected in substantial reading deficits of chronic cannabis users, even after 1 day of abstinence.

Above and beyond potential deficits based in the visuomotor stream of processing, we are also pursuing the possibility that there may be specific impairments in linguistic processing, involving stages from letter decoding to sentence-level comprehension. To this end, we systematically varied the frequency and length of specific target words that were embedded in declarative sentences. Previous research has consistently shown that frequent/short words are read faster than infrequent/long words (i.e., the word frequency/length effect, Rayner and Duffy 1986). More recent work has also suggested that the more basic visual effects of length and the more cognitive effects of frequency on word processing are relatively independent and thus well suited for a factorial design (e.g., Inhoff et al. 2003).

On the basis of our previous studies involving basic oculomotor tasks and visual search, we developed several specific hypotheses. First, we expected an increase of mean fixation durations in reading, reflecting the overall increase of saccade latencies in basic oculomotor tasks as a long-term effect of chronic cannabis use (Huestegge et al. 2009a). Second, analogous to the data from our previous visual search study (Huestegge et al. 2002), we anticipated an increase of regressive saccades back to previously inspected text resulting from working memory deficits. Third, in line with both previous studies, we examined whether saccade amplitudes are generally increased in the cannabis group. Finally, we assessed core skills of word processing during reading by comparing word length and frequency effects between groups. Our expectation was that deficits exhibited by chronic users would be more pronounced with increasing mental workload and complexity of processing.

Materials and methods

Participants

Eye movements in reading of 20 chronic tetrahydrocannabinol (THC) users with a minimum abstinence period of 24 h and an age of onset below the age of 17 were compared to those of 20 control participants without prior drug experience. The sample is identical with that of a previous report which focused on basic oculomotor tasks (Huestegge et al. 2009a). To qualify for chronic use, we requested a twice per week drug intake over the course of at least 2 years. To avoid shortcomings of prior studies (see Gonzalez et al. 2002), we only selected students that were academically successful members of the university community (undergraduate university students, RWTH Aachen University) without general cognitive deficits (IQ range, 107–137; M=118, SD=10). Mean age was 25 years (range, 19–45); six participants were female. An interview and a personality screening (MMPI-S) were conducted to exclude participants with neurological/psychiatric diseases, head injury, or experience with other drugs except nicotine, caffeine, and (modest levels of) alcohol. The control group (20 healthy students without any past or present drug history including cannabis) were matched in age (M=24 years), sex (six females), and educational/sociodemographic status (undergraduate university students; see Huestegge et al. 2009a, for further details). Informed consent was obtained from all participants.

Study protocol

The experiment was conducted immediately after a blood and urine screening (see Huestegge et al. 2009a, for further details). No cannabis or other drug consumption including alcohol was allowed 24 h prior to testing. Respective verbal self-reports were confirmed by subsequent blood and urine analyses. Tests of blood samples included routine laboratory parameters and measured the concentration of delta-9-tetrahydrocannabinol and its metabolites THCOH and THCCOOH via gas chromatography/mass spectrometry (cf. Moeller et al. 1992). THCCOOH is a long-lasting inactive metabolite, reflecting previous THC use even several days after modest drug exposure (Iversen 2000). The urine screening was conducted to test for drugs of abuse (benzodiazepines, barbiturates, amphetamines, ephedrines, morphine and related opioids, methadone, cocaine, and alcohol). The experiment lasted about 30 min.

Mean THC consumption duration in the THC group amounted to 9 years (SD=7.4). Participants smoked on average 10.5 joints per week and had accumulated lifetime doses of about 3,500 joints (SD=2,200). The age of onset of chronic cannabis consumption was similar between participants, ranging from the age of 14 to 16. The drug screening that was applied to the urine samples taken before the experiment indicated that none of the participants in the cannabis group had consumed any drugs in addition to cannabis. Their blood level of THC+THCOH was 1.7 ng/ml plasma (SD=1.7; range, 0–7.6). This value is quite low and very similar to the mean value of 1.9 (SD=3.7) reported in previous studies (e.g., Ehrenreich et al. 1999), underlining the credibility of the 24-h abstinence self-report.

Eye movement recording

Horizontal eye movements of the right eye during reading were recorded using a head-mounted infrared eye-tracking system (Eyelink I, SR Research Ltd.) with a sampling frequency of 250 Hz and a relative spatial accuracy in the order of few minutes of arc. Participants were seated in front of a 21″ cathode ray tube monitor and operated the space bar of a keyboard in front of them.

Materials

We selected 96 target words (nouns in basic form) according to a 2×2 design with the factors length and frequency. We classified four- to five-letter words as short and ten- to 11-letter words as long, and words with a frequency of <1 per million as being of low lexical frequency (M=0.50) and words with a frequency of >10 per million as being of high frequency (M=154, according to the Celex 1995 database). The resulting 4×24 items were fully orthogonal: frequency did not significantly differ between short vs. long words, neither for items of low mean frequency (M=0.49/million for short words and M=0.51/million for long words, p>.10) nor for items with high mean frequency (M=175/million for short words and M=133/million for long words, p>.10). All items were embedded in 96 active declarative sentences, each containing one item as a target word. Sentence contents were either completely neutral or referred to life in the arctic without resulting in a coherent story. This selection was based on a corpus of sentences used in a prior study to make sure that effects of target word length and frequency would be reliable (Radach et al. 2008). Sentence length varied from 70 to 82 characters. Target words were never positioned at the first or last two word positions in the sentence and were preceded by an adjective of six to ten letters in length. The post-target word had a fixed length of three to five letters. Target words were also controlled for their position in the sentence, number of syllables, subjective familiarity, orthographic regularity, and the number of morphologic components (see Radach et al. 2008 for a more detailed description of the materials).

Procedure

Participants were seated at a distance of 71 cm in front of a 21″ monitor (1,024×768 pixels, 100 Hz refresh rate). Sentences were presented on one central horizontal line on the screen, with each letter comprising a visual angle of 0.33° horizontally and maximum sentence length equivalent to a visual angle of 27°. Sentences were randomly presented one after another. A calibration of the eye-tracking system was executed prior to one out of ten sentences. Participants were asked to read the sentences silently at their normal pace for comprehension and to press a key when finished. At unpredictable intervals, a sentence was followed by a comprehension question (24 in total) which had to be responded to as precisely as possible. The questions were inserted to serve as a comprehension measure (see Huestegge et al. 2009b, 2010 for details on the scoring procedure). Seven practice sentences (plus two questions) were presented at the beginning of the experiment.

Data analysis and design

Data analysis focuses on two levels, using global measures that characterize the reading process more generally and local, word-based measures, allowing more fine-grained examination of target word processing. Global measures included mean sentence reading times, the percentage of regressions (interword saccades going from right to left against the normal reading direction), mean saccade amplitudes, and mean fixation durations. On target words, we determined initial fixation durations (duration of the first fixation on a word), refixation time (time spent on a word after initial fixation until it is left for the first time), rereading times (time spent on a word after it has been left for the first time), and initial landing positions of saccades within the word. Initial fixation durations and refixation times sum up to gaze durations, and gaze durations plus rereading times yield total reading times (see Radach and Kennedy 2004 for reviews of standard oculomotor measures in reading research).

We carried out independent samples t tests for group comparisons and mixed analyses of variance for the analyses of target word parameters with word length and frequency as within-subject variables and group as a between-subject variable. The critical alpha level was 5% throughout all analyses.

Results

Performance in text comprehension amounted to 79.41% (SD=9.43) in the cannabis group as compared to 87.13% (SD=8.44) in the control group, $t(38)=1.87$, $p<.05$. For the eye movement analyses, we implemented typical selection criteria for saccades and fixations (see, e.g., Radach et al. 2008), excluding fixations with durations <50 and >1,000 ms and those containing blinks (2.2% of all fixations), as well as saccades with amplitudes exceeding sentence length (1.2% of saccades).

Mean sentence reading time was significantly prolonged in the cannabis group (3,534 ms, SD=364) compared to the control group (3,243 ms, SD=556), $t(38)=1.93$, $p<.05$. The mean fixation duration was also increased in the cannabis group (248 ms, SD=27 vs. 231 ms, SD=20), $t(38)=2.25$, $p<.05$. There was no significant group difference for mean saccade amplitudes for saccades in reading direction (M=6.7°, SD=1.3), $t<1$. However, the cannabis group made substantially more regressions back to previously inspected text compared with controls (26%, SD=11 vs. 18%, SD=10), $t(38)=2.03$, $p<.05$.

In the following, we will focus on the more fine-grain eye movement parameters obtained from the well-controlled target words within sentences. Figure 1 depicts

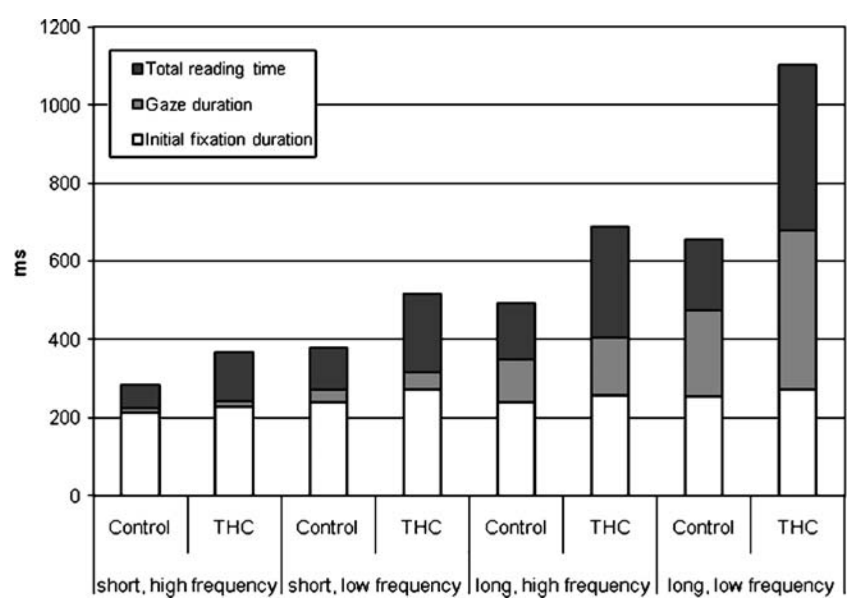

Fig. 1 Temporal reading parameters for short vs. long words of high vs. low frequency as a function of group. The figure is organized as a decomposition of total word reading time (corresponding to the total height of the bars) into three components: the duration of the initial fixation made on the word, the duration of all fixations made in addition during first pass reading before leaving the word (refixation time), and the duration of all fixations made on later passes after returning to the word (rereading time). Initial fixation duration and refixation time add up to gaze duration, and all three components combined are referred to as total reading time

initial fixation durations, gaze durations, and total reading times for the four target word categories and for both groups. Note that the figure is organized as a decomposition of total word reading time into three components: the duration of the initial fixation made on the word, the duration of all fixations made in addition during first pass reading before leaving the word (refixation time), and the duration of all fixations made on later passes after returning to the word (rereading time). Initial fixation duration and refixation time add up to gaze duration, and all three components combined are referred to as total reading time.

Initial fixation durations were greater for the cannabis group compared with controls, $F(1, 38)=7.88$, $p<.05$. There was also a significant main effect of word length, $F(1, 38)=16.72$, $p<.05$, and of word frequency, $F(1, 38)=87.38$, $p<.05$, indicating that the initial fixation duration is shorter for shorter than for longer words and for words of high vs. low frequency, respectively. There was no significant length by group interaction, $F<1$, indicating that the length effect did not differ between groups. However, the frequency effect was larger in the THC group, as indicated by a significant interaction of frequency and group, $F(1, 38)=4.14$, $p<.05$.

Refixation durations were also longer for the cannabis group compared with controls $F(1, 38)=5.64$, $p<.05$. As expected, we found significant length and frequency effects, $F(1, 38)=98$, $p<.05$ and $F(1, 38)=71$, $p<.05$ on gaze durations. Both effects were more pronounced for the cannabis group, $F(1, 38)=7.17$, $p<.05$ for the length by group interaction and $F(1, 38)=9.55$, $p<.05$ for the frequency by group interaction, respectively. The same pattern of results was also found for an analysis of refixations, that is the number of fixations on the word before the word is left for the first time.

Rereading times were also substantially longer for the cannabis group compared with controls $F(1, 38)=4.41$, $p<.05$. As expected, we found significant length and frequency effects, $F(1, 38)=27$, $p<.05$ and $F(1, 38)=32$, $p<.05$, respectively. Both the length and the frequency effect were much more pronounced for the cannabis group than for controls, $F(1, 38)=5.95$, $p<.05$ for the length by group interaction and $F(1, 38)=9.35$, $p<.05$ for the frequency by group interaction, respectively. Note that total reading time, defined as the sum of initial fixation duration, refixation time, and rereading time, almost doubled for cannabis users in some conditions (Fig. 1).

The initial landing position of saccades in the target word did not differ between groups, $F<1$. However, we found significant main effects of both length ($M_{short}=2.35$ letters vs. $M_{long}=3.80$ letters) and frequency ($M_{high}=3.00$ letters vs. $M_{low}=3.15$ letters), $F(1, 38)=214$, $p<.05$ and $F(1, 38)=7.67$, $p<.05$, respectively.

Discussion

Previous work provided evidence that chronic cannabis use leads to long-term deficits of the oculomotor control system (Huestegge et al. 2002, 2009a). In the present study, we asked to what extent such long-term deficits are also present in complex tasks that are important in daily life. More specifically, we focused on reading as an ecologically valid task that strongly relies on efficient eye guidance.

Overall, we found that the cannabis group exhibited increased sentence reading times associated with reduced text comprehension. However, such general data do not easily allow meaningful conclusions to be drawn with respect to the underlying sources of deficits. It was therefore essential to analyze eye movements in during reading in more detail to address specific hypotheses regarding the underlying mechanisms of the reading deficit.

One key finding of our analyses of general oculomotor measures is that mean fixation durations were increased by about 17 ms in the cannabis group. The effect size resembles the difference in saccade latencies of basic pro- and antisaccades that we reported in an earlier study with the same groups of participants (Huestegge et al. 2009a). Thus, it appears that the general slowing of saccade programming found in basic oculomotor tasks is also evident in mean fixation durations in more complex tasks like reading. This also corroborates an earlier study in which we reported a similar prolongation of mean fixation durations in a visual search task as a long-term effect of chronic use (Huestegge et al. 2002).

A second key finding is the increased rate of regressive saccades back to previously inspected text areas for the cannabis group. This finding is in line with a previous study that reported more frequent reinspections of previously fixated areas in a visual search task (Huestegge et al. 2002), and with the finding that in basic oculomotor tasks, chronic cannabis users had altered saccade amplitudes when they were asked to saccade to memorized screen positions (Huestegge et al. 2009a). In sum, these deficits point to a deficit in working memory performance, which is also one of the most consistently replicated deficits in studies of acute cannabis effects (e.g., see Fletcher et al. 1996; Lamers et al. 2006; Ploner et al. 2002; Rodgers 2000; Solowij and Battisti 2008; Solowij et al. 2002).

Interestingly, we did not find a group difference with respect to the mean saccade amplitude, or with respect to initial landing positions in words. Previous studies indicated that chronic cannabis users typically show increased saccade amplitudes in basic saccade tasks where saccade are not visually guided (Huestegge et al. 2009a) and also in a visual search task (Huestegge et al. 2002). Two explanations seem viable to account for our finding of no difference. It may be possible that a lifetime of experience with reading have led to the development of automatized scanning routines (Findlay and Walker 1999) that are immune to effects of intoxication which may appear in less familiar paradigms. Alternatively, an existing saccade size effect may be offset by a counteracting mechanism: previous research indicated that difficulties with text processing can be accompanied by smaller saccade amplitudes and initial landing positions located closer to the word beginning, reflecting a more “careful” reading strategy with increased processing load (e.g., Huestegge et al. 2009b, 2010; Radach et al. 2008). Thus, in our study, increased reading difficulties for the cannabis group may have cancelled out any potential increase of saccade amplitudes. However, on the basis of the present data, we certainly cannot rule out that saccade amplitudes in reading are not affected by cannabis use.

A final key finding of the present work is that long-term users of cannabis are characterized by substantial linguistic processing deficits during sentence reading. Assuming that the initiation of each individual saccade is delayed by a value in the order of about 20 ms overall, this difference is sufficient to account for the group differences in initial fixation durations for the target words. However, this mechanism certainly does not explain the much larger group differences in gaze durations and in total reading times, the latter showing an increase of up to 70% compared with controls (see Fig. 1). Gaze durations include all fixations made during first pass reading and are generally assumed to reflect processes of word recognition up to lexical access, the matching of letter information to a word representation stored in memory. The time spent rereading the same word after the eye had initially left is added to gaze duration to arrive at total reading time, the summed duration of all fixations ever made on the critical word. This measure is generally assumed to mainly reflect post-lexical processing on the sentence level such as syntactic parsing or integrating a word into a semantic sentence representation (see Rayner 1998; Clifton et al. 2007, for detailed discussions). Since we found substantial group differences with respect to all word viewing time measures, it is reasonable to conclude that all stages of word recognition and sentence comprehension, ranging from early to late processing, are affected by chronic use of cannabis. Critically, these difficulties of chronic users are amplified in measures reflecting higher level processing and when dealing with longer and less frequent words that demand substantially more mental workload to process. Here, in addition to impairments in working memory, the formation of an integrated sentence representation and, hence, components of long-term memory relevant for lexical access and comprehension appear to be affected.

One might argue that the observed adverse effects of cannabis are based mainly on group differences in general cognitive abilities or in the size of the verbal lexicon. In this study, we ensured that the cannabis group consisted of individuals with above average intelligence scores, thus avoiding serious limitations in previous studies (see Gonzalez et al. 2002). However, a shortcoming of the present study is that we had no direct access to IQ scores of the control group and thus cannot directly rule out a significant IQ advantage. Despite this fact, several considerations render a general cognitive group difference explanation of the reading differences rather unlikely. First, the mean IQ of the cannabis group was way above average (M=118), and only a mean IQ of 125 or above in the control group would yield a statistically significant group difference. However, the probability of randomly selecting a group of 20 participants with a mean IQ of 125 is way below .05, even if we take into account the fact that university students are sampled from an above average population mean IQ of about 115 (see Irwing and Lynn 2005 for this estimate of mean university students' IQ), z= 2.98, p=.003. Thus, it is extremely unlikely that our control group is characterized by a significantly greater IQ score. Furthermore, the size of the observed group differences in total reading times by far exceeds the standard deviations we usually observe in our laboratory (maximum about 200 ms) with similar sentence material in normal samples of university students, which should represent the normal range of reading and general cognitive abilities in university students (e.g., see Radach et al. 2008). This indicates that even if IQ differences between groups exist, these would likely not account for the whole size of observed group differences in total reading times of up to 450 ms. Second, the observed effects on linguistic processing were not restricted to words of low frequency but were also evident for high frequency target words (see Fig. 1), which represent highly familiar words that are easy to process. This rules out the possibility that differences in the size of the verbal lexicon account for the observed group differences. Third, since we compared the same groups of participants also with respect to basic visuomotor tasks (Huestegge et al. 2009a), we already know that the present cannabis group exhibits deficits in basic oculomotor control. Thus, it seems safe to assume that the observed differences in oculomotor control during reading are at least partly due to these basic deficits, acting in combination with specific linguistic processing deficits. Taken together, general or verbal IQ differences do not represent a plausible alternative explanation for the present findings, even though it seems advisable to directly assess general cognitive abilities in both groups in future studies.

Although the design of the present study qualifies for the assessment of long-term effects (Pope et al. 1995), further studies are needed with longer abstinence periods to directly determine the persistence of the impact of cannabis on both eye movement control in reading and linguistic processing. Furthermore, on the basis of the present results, it cannot be decided whether the deficits are irreversible (see Pope et al. 1995 for a critical discussion on irreversible effects) or whether they also hold for chronic users that started regular consumption after the age of 16. Further evidence for rather long-lasting effects would be a null correlation between THC and metabolite plasma levels and the deficits in the THC group, but the current sample of users is too small for meaningful correlations, especially for demonstrating null effects. However, in a previous study by Ehrenreich et al. (1999) which included a larger sample of chronic users (N=99), neither the estimated life-time dose nor THC plasma levels significantly correlated with RTs in a visual scanning task that involved eye movements as the central behavioral element. This finding can probably serve as indirect evidence for rather long-lasting impairments of the oculomotor system in chronic cannabis users. However, on the basis of the present data set alone, we are certainly unable to finally decide whether the observed effects are sub-acute effects of cannabis levels still acting after 24 h within the CNS or rather more long-lasting changes in brain function that occurred over months or years.

It could be argued that participants who are regularly consuming cannabis generally tend to react more slowly as a result of a relaxed attitude towards life or, alternatively, due to withdrawal symptoms. However, the data pattern of a previous report with the same sample of participants appears incompatible with a general slowing account, since we did not find increased latencies for all types of oculomotor responses. For example, saccade latencies in a task where participants were asked to withhold their response for a certain time interval did not differ between THC and control participants (Huestegge et al. 2009a). Finally, it is also unlikely that the observed reading deficits are based on different tobacco smoking habits between groups. Although tobacco is known to affect smooth pursuit performance (Sibony et al. 1988) and antisaccade errors (Powell et al. 2004), there is no indication that it prolongs saccade latencies. Instead, recent studies rather indicate reduced antisaccade latencies after nicotine consumption (Ettinger et al. 2009; Rycroft et al. 2007), whereas here, we rather observed a prolongation of fixation durations.

In sum, the present study demonstrated that chronic cannabis use is related to adverse long-term effects on reading. The analysis of eye movements revealed three distinct sources of the reading deficit: (1) a general slowing of the initiation of each individual saccade, (2) an impaired memory for recently inspected text and, most strikingly, (3) linguistic processing problems especially with respect to lexical access and post-lexical, sentence-level processing. The data pattern is consistent with our previous results in a visual search task (Huestegge et al. 2002). We would therefore like to suggest that the specific subtle cognitive long-term impairments of chronic cannabis use demonstrated in earlier studies (Croft et al. 2001; Fletcher et al. 1996; Lamers et al. 2006; Pope and Yurgelun-Todd 1996; Rodgers 2000; Solowij and Battisti 2008; Solowij et al. 2002) substantially scale up as task complexity increases, resulting in severely degraded performance of chronic cannabis users in all tasks involving visuomotor control, including spatial navigation (e.g., driving, see Warren et al. 1981), scene perception, and reading.

References

CELEX German Database (1995) Release D25. Computer software. Centre for Lexical Information, Nijmegen

Clifton C, Staub A, Rayner K (2007) Eye movements in reading words and sentences. In: Van Gompel R, Fischer M, Murray W, Hill R (eds) Eye movement research: a window on mind and brain. Elsevier, Oxford, pp 341–372

Croft RJ, Mackay AJ, Mills ATD, Gruzelier JGH (2001) The relative contributions of ecstasy and cannabis to cognitive impairment. Psychopharmacology 153:373–379

Ehrenreich H, Rinn T, Kunert HJ, Moeller MR, Poser W, Schilling L, Gigerenzer G, Hoehe MR (1999) Specific attentional dysfunction in adults following early start of cannabis use. Psychopharmacology 142:295–301

Ettinger U, Williams SCR, Patel D, Michel TM, Nwaigwe A, Caceres A, Mehta MA, Anilkumar AP, Kumari V (2009) Effects of acute nicotine on brain function in healthy smokers and non-smokers: estimation of inter-individual response heterogeneity. Neuro-image 45:549–561

Findlay JM, Walker R (1999) A model of saccade generation based on parallel processing and competitive inhibition. Behav Brain Sci 22:661–674

Fletcher JM, Page JB, Francis DJ, Copeland K, Naus MJ, Davis CM, Morris R, Krauskopf D, Satz P (1996) Cognitive correlates of long-term cannabis use in Costa Rican men. Arch Gen Psychiatry 53:1051–1057

Glass M, Dragunow M, Faull RLM (1997) Cannabinoid receptors in the human brain: a detailed anatomical and quantitative autora-diographic study in fetal neonatal and adult human brain. Neuroscience 27:299–318

Gonzalez R, Carey C, Grant I (2002) Nonacute (residual) neuropsy-chological effects of cannabis use: a qualitative analysis and systematic review. J Clin Pharmacol 42:48–57

Herkenham M, Lynn AB, Little MD, Johnson MR, Melvin LS, de Costa BR, Rice KC (1990) Cannabinoid receptor localization in the brain. Proc Natl Acad Sci USA 87:1932–1936

Huestegge L, Radach R, Kunert HJ, Heller D (2002) Visual search in long-term cannabis users with early age of onset. Prog Brain Res 140:377–394

Huestegge L, Radach R, Kunert HJ (2009a) Long-term effects of cannabis on oculomotor function in humans. J Psychopharmacol 23:714–722

Huestegge L, Radach R, Corbic D, Huestegge SM (2009b) Oculomotor and linguistic determinants of reading development: a longitudinal study. Vis Res 49:2948–2959

Huestegge L, Skottke EM, Anders S, Debus G, Müsseler J (2010) The development of hazard perception: dissociation of visual orien-tation and hazard processing. Transp Res Part F 13:1–8

Inhoff AW, Radach R, Eiter BM, Juhasz B (2003) Distinct subsystems for the parafoveal processing of spatial and linguistic processing information during eye fixations in reading. Q J Exp Psychol Hum Exp Psychol 56:803–827

Irwing P, Lynn R (2005) Sex differences in means and variability on the progressive matrices in university students: a meta-analysis. Br J Psychol 96:505–524

Iversen LL (2000) The science of marijuana. Oxford University Press, Oxford

Kennedy A, Radach R, Heller D, Pynte J (2000) Reading as a perceptual process. Elsevier, Oxford

Lamers CT, Bechara A, Rizzo M, Ramaekers JG (2006) Cognitive function and mood in MDMA/THC users, THC users and non-drug using controls. J Psychopharmacol 20:302–311

Moeller MR, Doerr G, Warth S (1992) Simultaneous quantitation of delta-9-tetrahydrocannabinol (THC) and 11-nor-9-carboxy-delta-9-tetrahydrocannabinol (THC-COOH) in serum by GC/MS using deuterated internal standards and its application to a smoking study and forensic cases. J Forensic Sci 37:969–983

Ploner CJ, Tschirch A, Ostendorf F, Dick S, Gaymard BM, Rivaud-Pechoux S, Sporkert F, Pragst F, Stadelmann AM (2002) Oculomotor effects of delta-9-tetrahydrocannabinol in humans: implications for the functional neuroanatomy of the brain cannabinoid system. Cereb Cortex 12:1016–1023

Pope HG, Yurgelun-Todd D (1996) The residual cognitive effects of heavy marijuana use in college students. JAMA 275:521–527

Pope HG, Gruber AJ, Yurgelun-Todd D (1995) The residual neuropsychological effects of cannabis. Drug Alcohol Depend 38:25–34

Powell JH, Pickering AD, Dawkins L, West R, Powell JF (2004) Cognitive and psychological correlates of smoking abstinence, and predictors of successful cessation. Addict Behav 29:1407–1426

Radach R, Kennedy A (2004) Theoretical perspectives on eye movements in reading: past controversies, current deficits and an agenda for future research. Eur J Cogn Psychol 16:3–26

Radach R, Rayner K, Kennedy A (2004) Eye movements and information processing during reading. Taylor & Francis, New York

Radach R, Huestegge L, Reilly R (2008) The role of global top-down factors in local eye-movement control in reading. Psychol Res 72:675–688

Rayner K (1998) Eye movements in reading and information processing: 20 years of research. Psychol Bull 124:372–422

Rayner K, Duffy SA (1986) Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity and lexical ambiguity. Mem Cogn 14:191–201

Rodgers J (2000) Cognitive performance amongst recreational users of “ecstasy”. Psychopharmacology 151:19–24

Rycroft N, Hutton SB, Clowry O, Groomsbridge C, Sierakowski A, Rusted JM (2007) Non-cholinergic modulation of antisaccade performance: a modafinil-nicotine comparison. Psychopharmacology 195:245–253

Sibony PA, Evinger C, Manning KA (1988) The effects of tobacco smoking on smooth pursuit eye movements. Ann Neurol 23:238–241

Soderstrom K, Johnson F (2003) Cannabinoid exposure alters learning of zebra finch vocal patterns. Dev Brain Res 142:215–217

Solowij N (1998) Cannabis and cognitive functioning. Cambridge University Press, Cambridge

Solowij N, Battisti R (2008) The chronic effects of cannabis on memory in humans: a review. Curr Drug Abuse Rev 1:81–98

Solowij N, Stephens RS, Roffman RA, Babor T, Kadden R, Miller M, Christiansen K, McRee B, Vendetti J (2002) Cognitive functioning of long-term heavy cannabis users seeking treatment. J Am Med Assoc 287:1123–1131

Stiglick A, Kalant H (1985) Residual effects of chronic cannabis treatment on behaviour in mature rats. Psychopharmacology 88:346–349

Warren RA, Simpson HM, Hilchie J, Cimbura G, Lucas DM, Bennett RC (1981) Characteristics of fatally injured drivers testing positive for drugs other than alcohol. In: Goldberg L (ed) Alcohol, drugs, and traffic safety (Vol. 1). Almqvist & Wiksell, Stockholm, pp 203–217