Study highlights

- The effect of helmet-wearing on cognitive performance under demanding conditions, so that small effects would become more detectible.
- One out of nine cognitive parameters showed a significant effect of helmet-wearing, disappearing in a post-hoc comparison.
- These results resolve previous disparate studies to suggest that, although helmets can be uncomfortable, any effect of wearing a helmet on cognitive performance is at worst marginal.

1. Introduction

The head is one of the most vulnerable parts of the body. Therefore, head protection is recommended, and often mandatory, for many professional and leisure activities. A helmet's main purpose is to protect against mechanical impact, e.g., for bicyclists, soldiers, and firefighters. Consequently, most scientific attention is spent on optimizing helmets to protect against mechanical impact (Aare et al., 2004; Cui et al., 2009; Deck and Willinger, 2006; Mills and Gilchrist, 2008). However, protective headgear is often associated with elevated local skin temperatures, unfavorable temperature perception, and discomfort (De Bruyne et al., 2008; Hsu et al., 2000; Li et al., 2008; Liu et al., 2008; Patel and Mohan, 1993; Skalkidou et al., 1999). This motivated several studies on the ergonomics of helmets, mainly focused on ventilation (Abeysekera et al., 1991; Bogerd and Brühwiler, 2009; Brühwiler et al., 2006; Reischl, 1986; Van Brecht et al., 2008). These studies started to take our understanding beyond the simple mechanics of impact protection to the wider issue of how a helmet affects its wearer.

A helmet is typically worn in situations with a higher likelihood for an accident and/or larger consequences if an accident occurs. Therefore, any tendency for a helmet to distract or otherwise reduce the performance of its wearer is undesirable, and could potentially obviate its protective effect by making potentially injurious incidents more likely to occur. Hancock and Warm (1989) have suggested a relationship between attention performance and stress. The stress in their model can be psychological as well as physiological in nature. This model explains several studies showing negative effects of fabric discomfort (Bell et al., 2003; Bell et al., 2005) and whole-body thermal discomfort on cognitive performance (Gaoua et al., 2012). Since helmets cause disturbances to the wearer, and affect the temperature of the scalp's surface, this raises the question whether a helmet might negatively affect cognitive performance.

Four studies have evaluated the effect of passive headgear on cognitive performance. Three of these studies used the same helmet that covered the scalp and ears but left the face uncovered (Hancock, 1983; Hancock and Dirkin, 1982; Holt and Brainard, 1976). One of these studies found increased reaction times on a dual task while wearing the helmet (Hancock and Dirkin, 1982). A more recent study found a negative effect on cognitive performance of wearing a cricket helmet during cricket practice (Neave et al., 2004). In contrast to these two studies, which showed an effect of headgear, on at least one of the cognitive parameters investigated, the other two found no effect of helmet wearing (Hancock, 1983; Holt and Brainard, 1976). This discrepancy might indicate that wearing a helmet has a minor effect of cognitive performance. In fact, the effect size (r^2) calculated from these publications is .02 (± .02), which is small in magnitude (Cohen, 1988).

The present study revisits the effect of a helmet on cognitive performance with a view to clarifying this contradictory literature. Since the effect of a helmet on cognitive performance is expected to be small, the present study aims at saturating the participants' attention capacity (Hancock and Warm, 1989), so that small effects cannot be buffered, and thus become more likely detectible. More specifically, 19 participants carried out a demanding cognitive test battery for 30 min in a repeated-measures study whilst wearing no helmet on one occasion and a helmet on the other. Unlike the open-faced helmets used in earlier studies, a full-face motorcycle helmet was employed for the present study representing a helmet design that covers the whole face, scalp and ears. This was to make the thermal and comfort effects of the helmet more extreme for the wearer. The measurements were carried out under warm (27.2 ± 0.6 °C) and wind-still conditions. One out of nine cognitive parameters showed a significant effect of helmet-wearing, and this effect was marginal, disappearing in a post-hoc comparison.

2. Materials and methods

2.1. Participants

Nineteen healthy male participants aged 28.3 (± 4.7) years (mean ± standard deviation) completed the study. The participants' head circumferences ranged from 53 cm to 62 cm. The exclusion criteria were the use of medications on a regular basis, or suffering from claustrophobia or an attention disorder. All participants were instructed to refrain from alcohol, drugs and caffeine 12 hours prior to each session. During familiarization sessions the participants were instructed to adjust their clothing in order to be thermally comfortable. As a result the participants wore jeans in combination with a long sleeved shirt or a T-shirt. The participants wore the same clothing during both experimental sessions. All participants gave informed consent before participation. This study was approved by the Cantonal Ethics Committee of St. Gallen (Switzerland).

2.2. Setup

The participants sat at the exit of a wind tunnel. A 19" LCD screen of 1280×1024 pixels was positioned just below the exit of the wind tunnel, allowing the participant to see the screen clearly (Fig. 1). A conventional keyboard and joystick (Attack 3, Logitech, Fremont, USA) were positioned in front of the screen. The vertical distance from the participant's head to the top of the wind tunnel was 5 (± 1) cm, and the horizontal distance from the end of the housing of the wind tunnel to the forehead was 8 (± 6) cm. This resulted in a viewing distance of 53 (± 6) cm from the eyes of the participant to the screen. During the sessions the participant was the only person occupying the chamber and did not have contact with the outside, nor had he any reference to time. All measurements were conducted in a climate chamber maintained at an ambient temperature of 27.2 (± 0.6) °C, and relative humidity of 41 (± 1)%. The wind speed (v_w) was 0.5 (± 0.1) m s^{-1} in order to have a minimal, but well-controlled v_w.

*** Fig. 1 somewhere here ***

2.3. Protocol

Each participant underwent five sessions. The time of day was kept constant to avoid any influences of the circadian rhythm. In order to reduce learning effects on the results, participants carried out three familiarization sessions. Subsequently, each participant underwent two experimental sessions in a balanced order. The first and last sessions occurred within two weeks, in order to prevent loss of familiarization. Before the start of each session the participant completed a mood questionnaire (Monk, 1989), and indicated the quality and quantity of their sleep during the previous two nights on two visual analogue scales. Finally, each session was finished with the assessment of whole body temperature perception on a nine-point scale (-4: very cold, to 0: neutral, to 4: very hot) and a five-point thermal comfort scale (0: comfortable, to -4: extremely uncomfortable). Both scales are detailed elsewhere (ISO10551, 2001).

The first 10 min of each experimental session were a familiarization session (Fig. 2). Each participant donned safety goggles (control: CON) or a helmet (intervention: HEL) at the start of this period and kept these on until the session was completed. More details concerning the helmets and goggles are given under Section 2.5. Following the familiarization, a 20 min equilibration phase started, the purpose of which was to achieve a thermal steady state. This period was previously found to be sufficient for this purpose (Bogerd et al., 2011). During this phase the participant read or carried out unrelated computer work. Finally, each participant completed the cognitive test battery.

The three separate familiarization sessions, preceding the experimental sessions, consisted of the first 10 min of an experimental session, and did not take place on the same day as an experimental condition.

*** Fig. 2 somewhere here ***

2.4. Cognitive tests

Visual vigilance and tracking test (VTT)

The visual vigilance and tracking test (VTT) consisted of a tracking and a vigilance task in parallel. The tracking task involved a red annulus that was presented in the middle of the computer screen, and a moving blue ball (Fig. 1). The ball received random impulses from the software, and the participant was instructed to keep it in the middle of the annulus, using the joystick to control the acceleration, direction, and amplitude. On the screen, the outer diameters of the annulus and ball were 4.3 cm and 2.6 cm, respectively. The vigilance component required continual observation of a black square in the center of the annulus which appeared to rotate 45° every 1 s. At random intervals the square was replaced by a black circle of similar size (diameter 1.1 cm); upon perceiving this change, the participant had to press the 'fire' button of the joystick as soon as possible. A random number of 125 (± 14) such circles were presented to the participant during a 30 min period. The following parameters were obtained from the VTT: (i) the mean absolute distance of the center of the ball to the center of the annulus, (ii) the mean reaction time to the appearance of the circular target, (iii) the number of correct detections of this target (defined as a response within 2 s of its appearance), and (iv) the number of false alarms (responses when the target had not appeared).

Auditory vigilance test (AVT)

The AVT presented the participants with a random sequence of two tones (2.5 kHz or 2.0 kHz) at 0.8 s intervals. At a random point in each 20 s interval, a sequence of three the same tones was presented. The participants were instructed to respond to these triplets as quickly as possible by pressing the spacebar on the keyboard. The following parameters were obtained: (i) reaction time, (ii) the number of correct responses (defined as a response within 2 s of the triplet), and (iii) the number of false alarms (responses when the target had not appeared). The tones were presented via in-ear phones (CX300, Sennheiser Electronic, Wedemark, Germany) which occupied little space outside the ear, in order to minimize problems fitting the helmet. Each participant chose the volume with which the tones were presented during the first familiarization session, and this was then kept constant over the remaining sessions. The AVT software was written in Matlab R2006b with use of the Psychtoolbox, version 3.0.8 (Brainard, 1997).

Letter cancelation test (LCT)

The letter cancellation test (LCT) consisted of six lines of 52 characters each, printed in 10 point Courier New type in landscape orientation over the full width of a white A4 page, with a 1 cm margin to the left and right of the text. Each line held nine 'K' and nine 'N' characters, randomly placed amongst other letters chosen at random. The task was to highlight all characters 'K' and 'N' using a marker, as quickly and accurately as possible. The time to completion and the number of correct responses were registered.

2.5. Intervention

During one experimental session the participant wore a helmet, while the other session served as a control condition in which the participant wore only goggles, as indicated in Fig. 2. In preparation for the first familiarization session, the participant was presented with the helmet size (as indicated by the manufacturer) corresponding to his head circumference, which was measured according to ISO8559 (1989). In addition, the participants chose the most comfortable model out of three comparable full-face motorcycle helmet models. These helmets have previously been characterized for their effect on heat loss (Bogerd and Brühwiler, 2008; Bogerd and Brühwiler, 2009), in those two studies, these helmets were coded as 130, 201, and 250. The helmets facilitate a similar heat transfer under the present wind still conditions. Furthermore, if the participant judged a given helmet to be uncomfortably tight or loose, the next appropriate size was used. During the sessions, the visor and vents of the helmet remained closed. During CON, the participant wore clear standard safety goggles (Astrospec 3000, Uvex, Fürth, Germany), in order to match the visual conditions experienced when looking through a motorcycle visor. The visor and goggles were cleaned before each use.

2.6. Statistics and data processing

The data collected during the 30 min VTT+AVT were evaluated as averages of six 5-min intervals for VTT and AVT. Repeated-measures multivariate analysis of variance (MANOVA) and generalized linear mixed models were employed for analyses as appropriate (further details below). Perception of comfort and temperature were compared using a paired t-test. Initial data processing was carried out with Matlab R2006b and analyses were carried out with SPSS 20.0.

3. Results

Mood, sleep quality and sleep quantity were indistinguishable between conditions. Generally, the cognitive parameters did not show an effect for the helmet intervention, whereas most parameters showed worsening performance with increasing time. Comfort was less favorable for HEL compered to CON (t_{18} = 3.92, p = .001, d = 2.10), with mean ratings of -1.7 (± 1.0) and -0.8 (± 0.6), respectively. In addition, temperature was perceived as warmer for HEL than CON (t_{18} = -5.29, p < .001, d = -1.21), with mean ratings of 1.9 (± 0.7) and 1.1 (± 0.8), respectively. Additional details are given below.

3.1. VTT+AVT

MANOVA was carried out on the VTT data, combining the dependent variables of displacement and reaction time into a single overall analysis of visuo-motor tracking performance. This showed an effect of Time on performance (Wilks's λ = .21, $F_{10,9}$ = 3.44, p = .038, η^2_p = .79) but no effect of Helmet (Wilks's λ = .96, $F_{2,17}$ = 0.34, p = .719, η^2_p = .04) and no Time × Helmet interaction (Wilks's λ = .61, $F_{10,9}$ = 0.58, p = .797, η^2_p = .39). Follow-up univariate tests of within-participants contrasts suggested a linear effect of Time on displacement scores such that mean displacement tended uniformly to increase with time spent on the task ($F_{1,18}$ = 12.72, MSE = 179.26, p = .002, η^2_p = .41) and a quadratic effect of Time on reaction time ($F_{1,18}$ = 5.75, MSE = 0.001, p = .028, η^2_p = .24), caused by a tendency for reaction times during the first and last 5-minute blocks to be shorter than in the middle four. The VTT data are given in Fig. 3, with the exception of the false alarms.

The AVT reaction time showed no effects of Time (Wilks's λ = .77, $F_{5,14}$ = 0.85, p = .537, η^2_p = .23) or Helmet (Wilks's λ = .96, $F_{1,18}$ = 0.81, p = .381, η^2_p = .04) and no interaction (Wilks's λ = .69, $F_{5,14}$ = 1.26, p = .333, η^2_p = .31). Fig. 4 gives the AVT data.

*** Fig. 3 somewhere here ***

*** Fig. 4 somewhere here ***

The accuracy data from the two tasks were analyzed using generalized linear mixed models with, as appropriate, Poisson error distributions and log link functions (for count data) or binomial error distributions and logit link functions (for proportions). Helmet use and Time were entered as fixed effects and a random effect term coded which scores were contributed by individual participants. The proportion of correct responses on VTT showed an effect of Time ($F_{5,216} = 11.47$, $p < .001$) but no effect of Helmet ($F_{1,216} = 2.97$, $p = .086$) and no Time × Helmet interaction ($F_{5,216} = 0.99$, $p = .422$). The Time effect was caused by a general decline in performance across the 6 5-min time blocks. Similar effects were seen for the VTT false alarms, in which the number of false alarms tended to increase across the Time blocks ($F_{5,216} = 7.22$, $p < .001$) but showed no relationship to Helmet ($F_{1,216} = 1.90$, $p = .169$) and no interaction ($F_{5,216} = 0.38$, $p = .866$). The proportion of correct responses on AVT similarly showed a Time effect ($F_{5,216} = 3.59$, $p = .004$), although only the first 5-min block differed from the last ($p = .035$), suggesting the effect of Time on this measure is small. There was also a significant effect of Helmet on the proportion of correct responses ($F_{1,216} = 4.64$, $p = .032$), but this too appears to be a minor effect, as a post-hoc contrast showed no difference ($p = .229$). The Time × Helmet interaction was not significant ($F_{5,216} = 1.29$, $p = .271$). Finally, the AVT false alarm count showed an effect of Time ($F_{5,216} = 4.83$, $p < .001$) but no effect of Helmet ($F_{1,216} = 1.30$, $p = .255$) and no interaction ($F_{5,216} = 1.84$, $p = .106$). For reasons that are not entirely clear, the Time effect in these data was carried by a higher number of false alarms in the second five-minute block than in the rest; other than this false alarm rates were comparable in each 5-min block.

3.2. LCT

MANOVA indicated that the combined time to completion and correct responses showed an effect of Time (Wilks's $\lambda = .70$, $F_{2,17} = 3.72$, $p = .046$, $\eta^2_p = .30$), but no effect of Helmet (Wilks's $\lambda = .89$, $F_{2,17} = 1.09$, $p = .358$, $\eta^2_p = .11$) and no Time × Helmet interaction (Wilks's $\lambda = .80$, $F_{2,17} = 2.20$, $p = .142$, $\eta^2_p = .21$). Follow-up univariate tests of within-participants contrasts suggested a linear effect of Time on the time to completion, indicating shorter time to completion following the VTT+AVT procedure than before ($F_{1,18} = 12.72$, $MSE = 129.37$, $p = .013$, $\eta^2_p = .30$). Fig. 5 shows all the LCT data.

*** Fig. 5 somewhere here ***

4. Discussion

This study attempted to resolve earlier mixed findings about the cognitive performance effects of wearing a helmet by using the most enclosed type of real-world helmet available and by making the cognitive tasks substantially demanding. These manipulations were intended to magnify any effects of wearing a helmet and so make them more visible. Under these harsh but realistic conditions the results suggest there is no substantial effect of a helmet on cognitive performance, even though subjectively participants found the helmet warm and uncomfortable.

Most of the cognitive parameters that were measured indicated a reduction in attentional capacity over time. Such time effects are typical (Grier et al., 2003; Taylor et al., 2008) and are the motivation behind recommendations that people should not attempt prolonged periods of cognitively demanding work in safety-critical situations. Such time effects are likely caused by a reduction in attention capacity (Grier et al., 2003; Hancock and Warm, 1989). An implication the presence of these time effects is that the cognitive tests and the protocol employed in the present study were sufficiently sensitive to changes in the participants' internal states. In addition, this suggests a meaning full level of sensitivity on cognitive performance, also if they would be caused by helmet-wearing.

A potential drawback of cognitive examinations in which a participant carries out more than one task is the possibility of shifts in attention from one task to the other. To evaluate attention shifts between VTT and AVT, for each 5-min block a single value was calculated for each test. This was achieved as follows: First, the 30-min mean was subtracted from each 5-min interval for each participant; second, the sign was corrected for each parameter so that negative values represented worse performance relative to the 30-min average, and vice versa; third, these differences were divided by the SD obtained from the entire 30-min interval; finally, the mean was taken from these normalized differences for all participants and parameters. For both VTT and AVT, Pearson's correlations were calculated between these new measures for each participant, after applying linear detrending. If participants had switched attention from one task to another there should be negative correlations in these data. This analysis gave r = .21 (± .26), with a nonsignificant correlation in 17 out of 19 participants. Therefore, the fluctuations in VTT are in general not related to fluctuations in AVT, suggesting attention shifts did cause increased variance in the VTT and AVT data. The lack of substantial correlations in these data also suggests that VTT and AVT consume a different attention capacity, a common finding in the cognitive literature (Brooks, 1968; Hirst and Kalmar, 1987).

The present results are in line with two previous studies, which did not find an effect of passive headgear on cognitive performance (Hancock, 1983; Holt and Brainard, 1976). The former study used a simple arithmetic addition task, whereas the latter used a simple reaction time task. In contrast, the two other studies mentioned in the Introduction reported at least one measured cognitive parameter being affected by wearing a helmet (Hancock and Dirkin, 1982; Neave et al., 2004). Hancock and Dirkin (1982) used a central and peripheral visual choice reaction time, whereas Neave et al. (2004) used an extensive proprietary cognitive test battery. This pattern of findings across the four earlier studies could suggests that any effect of wearing a helmet is sufficiently subtle that it can only be seen when people's cognitive resources are highly taxed.

The question, then, is why the present study, which arguably taxed participants more than in any previous study, found no real effect of helmet-wearing on cognitive performance. The four earlier studies all used a similar type of helmet, which was more open than the full-face, visored helmet used in the present study. However, it is not clear why this should lead to less interference in this study than the previous studies. Neave et al. (2004) used a notably different population to all the other studies (youths, with a mean age of 14.3 ± 4.0 years), and had their participants undertake 30 min of physical exercise, which both make their study stand out from the rest. But whilst these differences could plausibly explain Neave et al. (2004) showing different results to the present study, it cannot explain why Hancock and Dirkin (1982) found an effect of helmet-wearing when this study did not.

Most plausibly, the explanation for the overall pattern of results across these studies and the present study lies in helmet-wearing having a marginal effect on cognitive performance. Hancock and Dirkin (1982) measured a total of eight parameters but only report an effect of helmet-wearing on one. Neave et al. (2004) only found a helmet effect after their individual cognitive performance parameters were combined into composite measures. Their individual cognitive parameters did not show significant effects of helmet-wearing (Neave, 2008, personal communication). The present study found an effect of wearing a helmet on one out of a total of nine cognitive parameters, and even then, this parameter did not remain significant in a post-hoc test. Thus, it appears that if a helmet does cause an impairment of cognitive performance, such effects are small, and undetectable under well-controlled laboratory conditions. It is unlikely that such marginal effects, if any really exist, will have real-world implications for safety. Small effects, of the type we are suggesting here, are difficult to measure, and increase the risk of a Type 2 error. Therefore, a power analysis was carried out to verify the sensitivity of the present study in detecting small effects. The effect size for each of the cognitive parameters was calculated using G*Power 3.1.2 using: $\alpha = .05$, $\beta = .20$, $N = 19$. All other necessary inputs were directly derived from the data collected. The approach was to quantify, for each cognitive parameter measured in this study, the smallest effect size that our procedure and participant pool could detect. This analysis showed that, on average, we had sufficient power to detect effect sizes of $r^2 = .03$ (± .02) or above. In the worst case, for the reaction time on the AVT, the present design has sufficient power to detect an effect size of $r^2 = .06$ or above. Thus, the present study was able to measure small effects (by the criteria of Cohen, 1988) on cognitive performance had any existed.

5. Conclusions

The present study assessed the effect of wearing a full-face helmet on cognitive performance under realistic but demanding conditions. One out of nine cognitive parameters showed a significant effect, and this effect was marginal, disappearing in a post-hoc comparison. These results, together with previous studies, suggest that although people find wearing helmets in warm conditions subjectively uncomfortable, if wearing a helmet does impair cognitive performance, the effect is at worst marginal.

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8. Figure captions

Fig. 1. The setup with a participant carrying out the simultaneous visual vigilance and tracking test (VTT) and auditory vigilance test (AVT). The helmet shown here was not used in the study.

Fig. 2. The protocol and interventions in an experimental session. VTT: vigilance and tracking test, AVT: auditory vigilance test, and LCT: letter cancellation test.

Fig. 3. The results for the vigilance and tracking test (VTT) parameters (a) displacement, (b) response time, and (c) correct responses. The data is represented as averages of 5 min intervals, the error-bars indicate the SEM.

Fig. 4. The results for the auditory vigilance test (AVT) parameters (a) response time, (b) correct responses, and (c) false alarms. The data is represented as averages of 5 min intervals, the error-bars indicate the SEM.

Fig. 5. The results for the letter cancelation test (LCT) parameters (a) time to

completion, and (b) correct responses. The LCT was carried out before and following the VTT+AVT (Fig. 2), the error-bars indicate the SEM.

Figure 1
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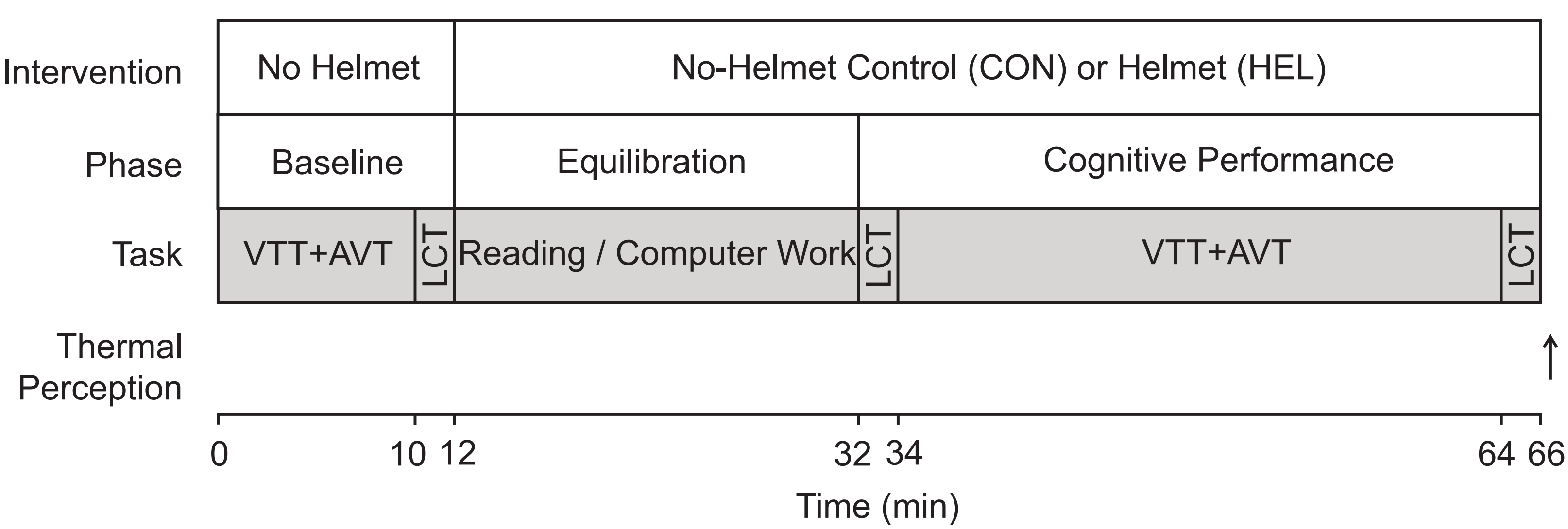
Figure 2



Intervention
No Helmet
No-Helmet Control (CON) or Helmet (HEL)
Phase
Baseline
Equilibration
Cognitive Performance
Task
VTT+AVT
LCT
Reading / Computer Work
LCT
VTT+AVT
LCT
Thermal Perception
0
10
12
32
34
64
66
Time (min)

Figure 3
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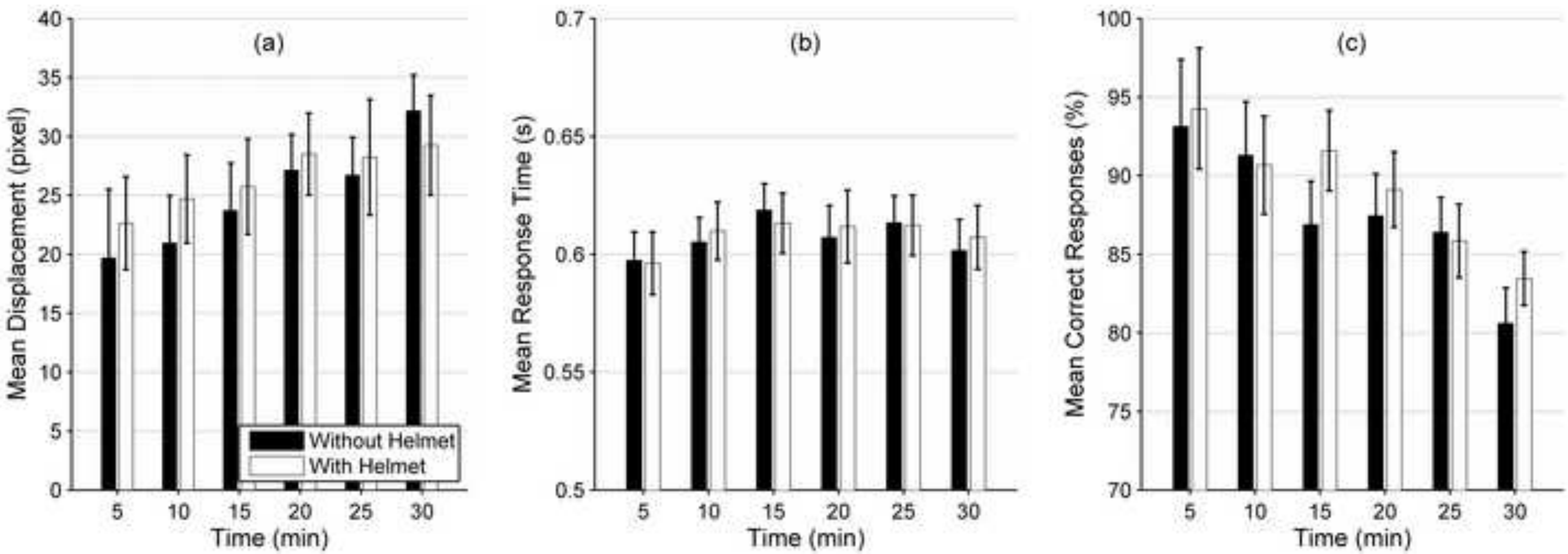

Figure 4
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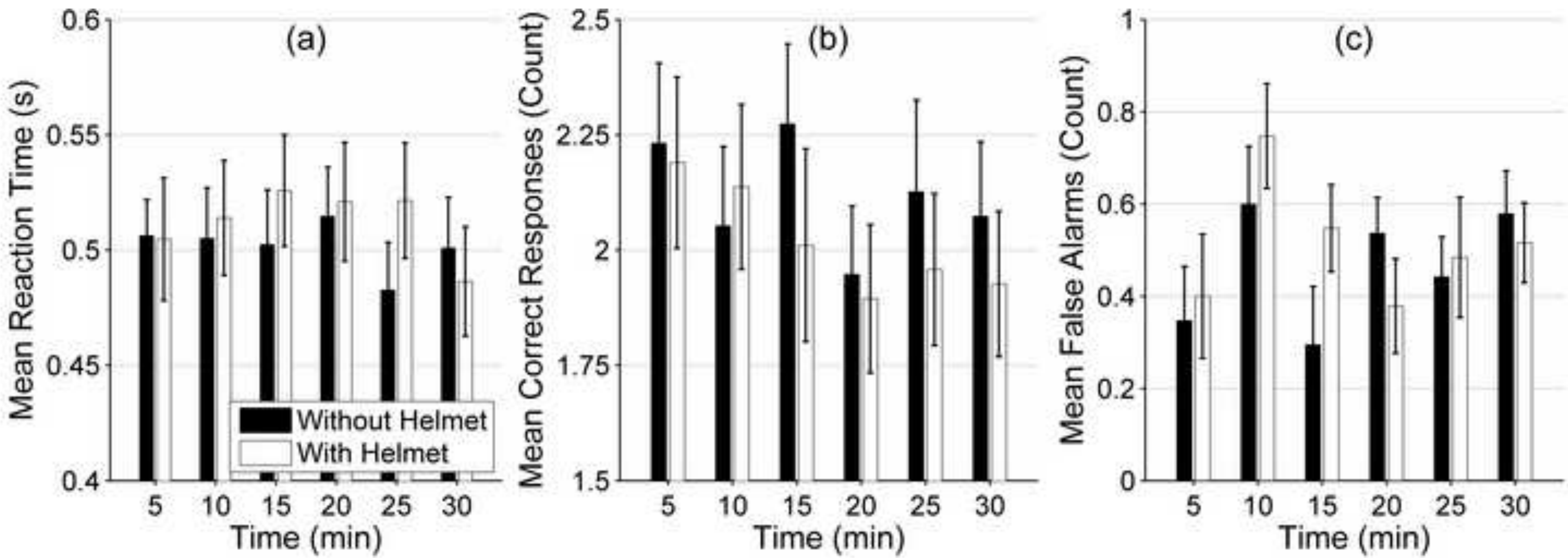

Figure 5
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