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Lethal smothering with a pillow – How 181 music festival visitors tried to kill a dummy



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ABSTRACT

Purpose: Smothering to death is most often done with a soft cover, such as a pillow. This is one of the hardest to diagnose causes of death. Knowing more about how people perform such an act and whether there is any correlation between perpetrator characteristics and smothering approaches may help in solving criminal cases involving smothering.

Methods: A total of 181 visitors of a music festival were asked to smother a dummy with a pillow. Each participant provided their age, gender, dominant hand, length, weight, alcohol use (last 24 h) and drug use (last 24 h) in a questionnaire. Forces applied by the participant on the dummy head with the pillow were continuously measured and the smothering modus operandi (described by aspects such as the placement of the hands, feet and body weight) was obtained from video recordings.

Results: Participants with high alcohol consumption provided higher smothering forces. Increases were also found for taller participants and those who had used drugs. Smothering seemed most effective when placing both hands on the pillow on the head and when placing the center of mass as much directly above the dummy head as possible. A stable, central stance also benefitted smothering effectiveness.

Conclusion: Forensic case work may potentially benefit from these results in the future by linking the current results to the location of hand and finger marks on a pillow.

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1. Introduction

Smothering to death is an often encountered cause of death in murder cases and is defined as suffocation caused by an obstruction of the air passage [1]. In suffocation cases it is often hard to distinguish homicide, suicide and accidents based on physical traces. Of the many possible MOs (modus operandi) and materials, smothering with a soft cover (such as pillows, handkerchiefs or towels) is the most commonly used, while also being the most difficult to diagnose [2]. Typical smothering victims are infants, elderly, disabled, or people restrained by illness, alcohol or drugs. Because these victims are unable to defend themselves effectively, trace evidence is usually very subtle and injuries are often minor [2–4]. Fibers recovered from the victim's

mouth, nose or face may identify the object used for smothering, such as a pillow. The number of fibers found may help to distinguish between criminal and legitimate actions (such as sleeping on a pillow) [5]. Hand and finger marks left on the smothering object may provide information about how the object was handled [6,7].

De Ronde et al. [6] previously showed in a volunteers study that the distribution of hand and finger marks is well-distinguishably different on pillowcases around pillows used for smothering as compared to pillowcases only touched when changing the pillowcase. However, these data did not provide any information about how the volunteers conducted the smothering in terms of pillow handling, body positioning and posture or amount of force applied. Taking these aspects into account may help finding any relations between suspects' characteristics and smothering forces and smothering MOs, which may eventually enable forensic investigators to determine from hand and finger marks how a pillow used for smothering was handled, with how much force and perhaps even by what kind of person. Therefore, the aim of this study was to explore what MOs, postures and forces are used by

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Fig. 1. Overview of the setup used for the smothering experiment. The wooden dummy head rested on a force measuring unit, which is described in Fig. 2.

volunteers mimicking smothering and how these aspects relate to volunteers' characteristics.

2. Materials and methods

At the music festival Lowlands 2016 (19–21 August 2016, Biddinghuizen, the Netherlands) 181 participants were asked to simulate a smothering act with a pillow on a dummy. The experiment was carried out by the authors in cooperation with the University of Applied Sciences (Amsterdam, the Netherlands), Netherlands Forensic Institute (the Hague, the Netherlands) and Dutch Police Academy (Apeldoorn, the Netherlands) and was the same as the one from which the data of de Ronde et al. [6] was obtained as part of the Lowlands Science experiments. Ethical approval was obtained from the Human Research Ethics Committee (study number 46) of the university to which the corresponding author is affiliated.

Prior to the experiments, participants were briefed, signed an informed consent form and filled in a digital questionnaire covering age, gender, dominant hand, length, weight, alcohol use (last 24 h) and drug use (last 24 h). No data were collected that could lead to identification of any of the participants. The participant next conducted two tests in randomized order in different rooms: smothering the dummy with a pillow and changing a pillowcase. The latter was used to investigate if finger marks on pillowcases used for smothering can be distinguished from those on pillowcases only used for normal activities, which was described elsewhere [6] and will not be discussed further.

2.1. Test setup

In a blinded room a dummy, sized like an adult male, was laid face up on a single bed, with a blanket and sheet covering its body (Fig. 1). The bed was situated such that the floor space was equal on both sides of the bed. A video camera recorded the smothering without having the participant's face visible. The dummy head was made to move freely with respect to the body and was fixed on a metal pin running through the mattress and bed. The metal pin rested via a spring (Fig. 2) on a load cell (Futek LCM300, 2 kN, FUTEK Advanced Sensor Technology, Inc., Irvine, CA, U.S.A.). Contrary to what is mentioned erroneously in de Ronde et al.

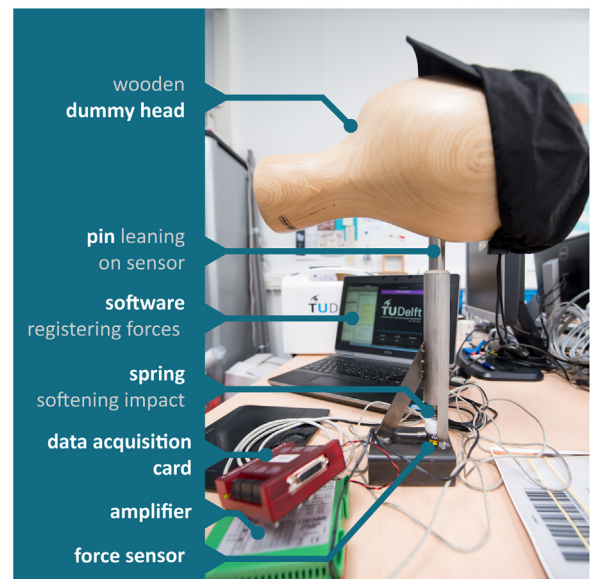


Fig. 2. Force measurement setup used to measure the amount of force exerted by participants on the dummy head with the pillow. A detailed specification of the used electronics is given in the text.

[6], no pressures, but only resulting vertical forces on the dummy head were measured. The sensor signals were amplified (Scaime CPJ RAIL, SCAIME, Juvigny, France), converted to digital signals (Labjack U3-HV, Labjack co., Lakewood, USA) and sent to a measurement PC with data acquisition software custom-made in Matlab (Mathworks, Natick, USA).

2.2. Smothering test thresholds

In real smothering situations fully blocking someone's airways may require quite high forces, especially if the victim resists. Making a test dummy that would struggle in resistance would not only be complex and create a more dangerous test situation, but would also have been deemed unethically realistic and possibly traumatic by the ethics board. Therefore, in order to make all participants put in considerable and a somewhat standardized

effort during smothering a threshold force was set for the minimum force required to mimic blocking the airways. This threshold was determined by having the lead investigator (victim) rest with his head on the pin of the dummy head. Another investigator (perpetrator) placed the pillow used for the experiments (see section “Test Protocol”) on the victim’s face and started pushing down carefully with increasing force. The victim held his arm up, holding a metal rod and lowered his arm if he wasn’t able to breathe. The force at that instance was noted and the perpetrator directly removed the pillow. Letting the victim hold the metal rod was a safeguard to ensure that if he would faint this would instantly be noticed. An average threshold force of 150 N was set based on this test.

A fitting threshold time was set to ensure that all participants would put in prolonged effort, which would often make them change position after a while or change their smothering behavior in order to be able to keep up the required force. Information in web and dark web sources suggested that about 3.5 min of smothering would be necessary to commit murder by smothering with a pillow, while the time required for smothering a person until unconsciousness is about 5 min according to other sources [8–10]. For pragmatic reasons and because 30 s of fierce smothering already proved to be quite tiring in pilot tests, a standard smothering time of 45 s was chosen. In the experiment, all participants had to input identical impulses: $45\text{ s} \times 150\text{ N} = 6750\text{ Ns}$, so harder pushing resulted in a lesser required smothering time and a quicker finished test. The user interface of the software continuously showed and recorded the applied forces and impulse and warned the test supervisor with a brightly colored full-screen message if the participant was pushing under the force threshold and thus had to be encouraged to push harder.

2.3. Test protocol

Before each smothering test, the participant’s hands were washed, dried and then painted with three skin-compatible UV-paint colors (PaintGlow Neon UV Face and UV Body Paint); blue (AA1B03) on the fingers, pink (AA1B04) on the palms, yellow (AA1B01) on the thumbs (Fig. 3). The participant was then handed a clean pillow (Ikea AXAG, $60 \times 70\text{ cm}$, 590 g pillow in a washable hospital pillow, $60 \times 70\text{ cm}$, obtained from <https://www.zorgmatras.com/waterdicht-kussen.html>) in a clean black pillowcase (IKEA DVALA black, $60 \times 70\text{ cm}$, 100 % cotton, thread density 152) and instructed to enter the smothering room and stand at the foot end of the bed, received further instructions and was then allowed to start. Participants were free to choose from which side



Fig. 3. Researcher applying UV-paint to the hands of a participant: pink on the palms, blue on the fingers and yellow on the thumbs (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

of the bed to approach the dummy head, where and how to position themselves and how to use the pillow for smothering.

Participants were told to keep applying as much force as they could until the test supervisor would indicate that they had put in sufficient effort. If the test supervisor received a software alarm that the participant was not pushing hard enough, the participant was encouraged to keep pushing harder. Once the participant had input 6750 Ns the software on the measurement PC indicated that the test was completed and the test supervisor told the participant to let go of the pillow by leaving it where it is, removing their hands and stepping away from the bed. Participants could call for a break if they felt the need to pause the experiment, ask something or stop. In that case the measurement system could be paused and continued later. The number and duration of breaks were recorded separately by the system.

The separate datasets of each participant were coupled using a unique 4-digit code on a set of identical barcode stickers. Such a sticker was scanned to start and label the questionnaire, filmed at the start of the video, scanned to start and label the force measurements, stuck on the pillowcases the participant used and photographed together with the fingerprints afterwards.

2.4. Data collection and analysis

Thirty video recordings were analyzed to find parameters that could be used to categorize smothering MOs. Next, these parameters were extracted for all video recordings by authors DP and AJL individually. Whenever these investigators produced different outcomes, their results were discussed afterwards and consensus was found by reviewing the videos again. In case not all parameters could be extracted from the videos because of the limited view of the camera, that participant was excluded from all analyses.

From the measured force data five variables were obtained and used from each test for further analysis, as listed and explained in Table 1. Data from the questionnaires was used to obtain demographics and investigate any effects of participant’s sex, build and alcohol or drug use on their smothering forces and MOs. In case one or more fields in the questionnaire were left blank, that participant was excluded from all analyses. Questionnaire and force data were statistically assessed in SPSS (IBM SPSS statistics 25) using univariate general linear modelling (GLM) with a significance level (p) of 0.05, as it can detect linear and non-linear relationships between variables and is robust for unequal group sizes. The factors used for GLM testing were F_{mean} , F_{max} and $t_{smother}$. Because of the chosen smothering effort standardization, F_{mean} and t_{valid} were inversely proportional: their product was always about 6750 Ns (with round-off and timing errors causing minor variations). Therefore, F_{mean} was used in the statistical analysis, as this is the driving variable most directly depending on the participant’s behavior, and t_{valid} was left out. The Kolmogorov Smirnov test was used to test the data for normality.

3. Results

A total of 181 participants took part in the experiment. During the video analysis, 29 were excluded, leaving 152 for further analysis:

- Six were excluded because some of the linked data was missing (which happened if a participant forgot to fill in the questionnaire first, did fill in the questionnaire but decided not to partake in the smothering test, or if the video camera wasn’t turned on);
- Fourteen were excluded because one or more parameters of their smothering MO could not be seen in the video recordings;

Table 1
Smothering force and time variables measured for analysis.

Variable name	Explanation
$t_{smother}$ [s]	Running time from the start of smothering (first measured force) to the end of smothering (last measured force), excluding any eventual breaks.
t_{valid} [s]	Time of valid smothering above the threshold of 150 N
F_{mean} [N]	Mean smothering force above the threshold of 150 N
F_{max} [N]	Maximum smothering force
$Eff_{smother}$	The smothering efficiency; ratio between $t_{smother}$ and t_{valid} .

- Three were excluded for missing gender information in the questionnaire;
- Six were excluded after being identified as unrealistic outliers in the force data:
 - o One participant could not keep up the force and had to pause, but the test operator forgot to pause the measurement, causing the time data to be flawed;
 - o During analysis of the force data, the data of two participants with too little force or stamina were excluded for being outliers with exceptionally long smothering times;
 - o Three others were excluded for being outliers with exceptionally high mean or max forces due to giving short, hard blows to the dummy head, causing impact contact peak forces on the force sensor, preventing measuring the actually applied smothering force.

The full dataset is provided in Appendix 1 as an overview of the included data and as a data file, complete with all excluded data, the used questionnaire and all briefing and debriefing forms in [11]. Table 2 shows the characteristics of the included participants as obtained from the questionnaire. Participants' ages ranged from 18 to 62 years (mean 27.8, STD 8.2). All data showed to be not normally distributed, but skewed (Fig. 4).

Table 2
Study population characteristics.

Category	Number
Gender	
Male	73
Female	79
Handedness	
Left	23
Right	129
Length [m]	
1.51 – 1.60	6
1.61 – 1.70	38
1.71 – 1.80	56
1.81 – 1.90	37
1.90 – 2.00	15
Weight [kg]	
< 60	20
61 – 70	49
71 – 80	34
81 – 90	23
91 – 100	16
> 101	10
Alcohol use in past 24 h [glasses]	
0	18
1 – 5	58
6 – 10	42
11 – 15	21
15+	11
No answer	2
Drug use in past 24 h	
Yes	36
No	116

3.1. Smothering forces

Table 3 provides the descriptive statistics of F_{mean} and F_{max} for males, females and all participants grouped. As participants had

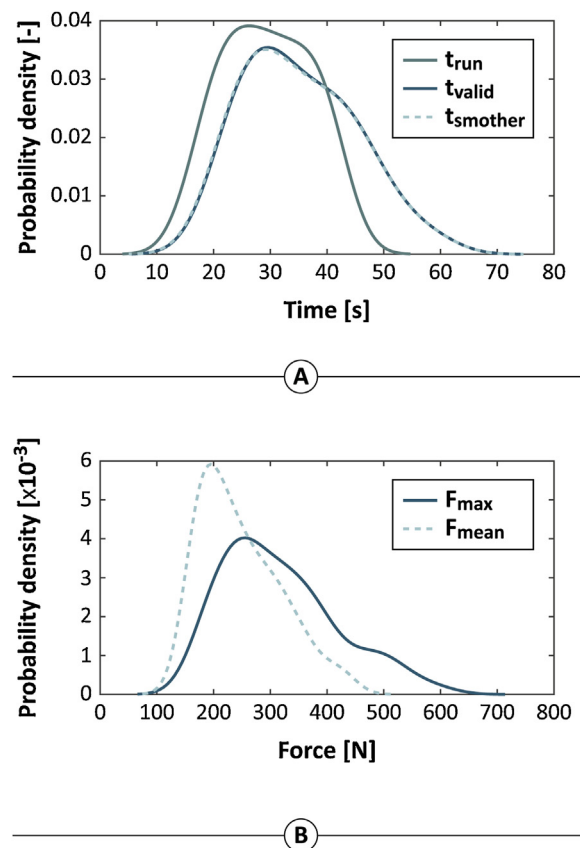





Fig. 4. Probability densities for **A)** run times (t_{run}), smothering times above the smothering threshold (t_{valid}) and total smothering times ($t_{smother}$) and **B)** maximum (F_{max}) and mean (F_{mean}) exerted smothering force.

Table 3
Smothering forces for total study population and per gender.

Total	F_{mean}	F_{max}
Total study population (N = 153)		
Mean [N]	247	317
Median [N]	231	302
Std. Deviation [N]	703	997
Minimum [N]	157	177
Maximum [N]	433	602
Males (N = 74)		
Mean [N]	254	316
Std. Deviation [N]	751	1009
Females (N = 79)		
Mean [N]	241	317
Std. Deviation [N]	654	994

Table 4

Smothering MO aspects extracted from the observation videos. For each aspect (left column bold type), the codes used in the data tables to mark different variants are provided in bold italic type between brackets after the explanation. Photos used to illustrate some of the aspects are video stills from the experiment recordings.

Aspect	Explanation and variants		
Approach – side	Side of the bed from which the participant approached the dummy head: left (<i>L</i>), right (<i>R</i>), middle (<i>M</i>).		
Body – placement	Side at which the participant was situated during smothering: left (<i>L</i>), right (<i>R</i>), middle (<i>M</i>).		
Legs – placement	Placement of the legs during smothering: both feet on the floor (<i>FF</i>), a foot on the ground and a knee on the bed (<i>FK</i>), both knees on the bed (<i>KK</i>).		
Hands – main placement	Main position of the hands on the pillow during smothering:		
both next to dummy head (<i>NH</i>)	one next to, one on dummy head (<i>NHOH</i>)	both on dummy head (<i>OH</i>)	
			
Hands – switching	Sequence of hand placement repositioning. Registered by noting the aspect 'Hands – main placement' each time it changed and each time a participant released their grip to reposition the same placement. For example: <i>NH-NHOH-NH-NH</i> means: NH placement - transition to NHOH - transition back to NH placement - release and regain NH placement		
Arms – posture	Main posture of the arms during smothering:		
	stretched (<i>S</i>)	bent (<i>B</i>)	
			
Body weight – position:	Main positioning of the center of mass during smothering;		
chest above dummy head (<i>CC</i>)	shoulders above dummy head (<i>SS</i>)	head above dummy head (<i>HH</i>)	
			

to push beyond the 150 N threshold, F_{mean} was above this threshold for all participants.

3.2. Smothering MOs

From the video data seven aspects were established to describe the characteristics of the smothering MOs of all participants (See Table 4). During the experiments the aspects 'Approach – side' and 'Body – placement' appeared to be potentially biased due to the location where the test supervisor and equipment were situated. Despite ensuring the same amount of space on each side of the bed, having the participants always start at the footboard of the bed, and explicitly instructing all participants that they were free to choose their approach, only six participants choose the right-hand side of the bed. Furthermore, the aspect 'Hands – switching' varied much between participants, did not show many consistent grouping options and mainly seemed to be an indicator for difficulty of getting a proper grasp, of getting a stable position, or of finding and keeping up sufficient force. Therefore, these three aspects are provided in Appendix 1 and [11], but were left out of the statistical analysis for this report.

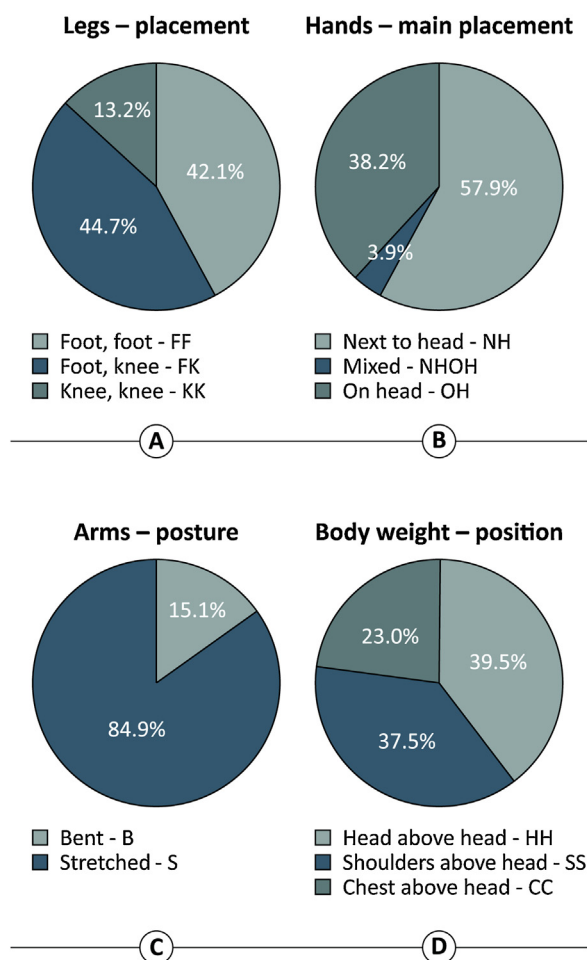


Fig. 5. Distribution of the different smothering MO's applied by the participants. **A)** Placement of the participants' legs. 'Foot' indicates a foot placed on the floor and 'Knee' indicates a knee placed on the bed. **B)** Placement of the participants' hands. 'Mixed' indicates that one hand was placed on the dummy head and one was placed next to the dummy head. **C)** Posture of the participants' arms. **D)** Positioning of the participants' body weights, described by indicating which body part was positioned most directly above the dummy head.

Fig. 5 shows the participants' smothering MOs described by the aspects 'Legs – placement', 'Hands – main placement', 'Arms – posture' and 'Body weight – position'. In Appendix 2 a crosstab is provided showing how often which combinations of MOs occurred as an overview and as a data file in [11]. The majority (87 %) of participants had at least one foot next to the bed. Standing with both feet next to the bed was preferred by about twice as many women as men, while almost twice as many men as women preferred leaning with one knee on the bed. Having at least one knee on the bed did show to provide better body weight placement over the dummy head.

Slightly more participants chose to put both hands on the head (OHOH) than both hands next to the head (NHNH) during smothering. Only a small minority used one hand on and one hand next to the head (NHOH). In this group, 12 out of 15 participants used their preferred hand to push on the head (Table 5). Participants using the NHOH placement always had at least one foot placed next to the bed. By far the most participants applied the smothering force mainly with stretched arms and a minor group used mainly bent arms.

3.3. Relations between smothering force and time and other parameters

The effects of the tested factors obtained from the survey and tested smothering MO aspects that showed to be significant are described below. Fig. 6a illustrates the significant effect ($p = 0.01$) of alcohol use on F_{mean} , with high consumption leading to higher force. Similarly, taller participants and participants who had used drugs showed a significantly decreased $t_{smother}$ due to higher smothering forces (Fig. 6b and c). No statistically significant effects of any of the tested variables on the smothering efficiency were found.

F_{mean} , F_{max} and $t_{smother}$ were significantly affected by the aspects 'Hands – main placement' ($p < 0.001$ for all three variables) and 'Body weight – position' ($p < 0.001$ for F_{mean} and F_{max} and $p = 0.010$ for $t_{smother}$). Forces were highest when both hands were placed on the head and lowest when both were placed next to the head, which logically resulted in the inverse for $t_{smother}$ (Fig. 7). The closer the center of weight of the participant (located in the abdomen) was positioned to being straight above the head, the higher the applied smothering forces were and the quicker the smothering was completed. Leg placement with either both legs next to the bed or two knees on the bed occurred with higher maximum forces than when one leg was placed next to the bed and one knee on the bed.

Table 5

Handedness versus hand placed on the dummy head of participants who placed one hand on and one hand next to the dummy head. *Italic type indicates that the non-preferred hand was placed on the dummy head.*

Participant Nr.	Handedness	Hand on head
2089	Right	Right
2100	Right	Right
2138	Right	Right
2172	Right	Right
2104	Right	Right
2101	Right	Right
2129	Right	Right
2157	Right	Right
2169	Right	Right
2171	Right	Right
2025	Right	Right
2057	<i>Left</i>	<i>Right</i>
2062	Right	Right
2206	<i>Right</i>	<i>Left</i>
2242	Right	<i>Left</i>

4. Discussion

The results from the presented experiments provided insight in the MOs and exerted force of volunteers simulating forceful smothering with a pillow. The alcohol intake of the participants seemed to stimulate the application of higher smothering forces. This might be explained by a reduction of self-control due to alcohol intake. The intake of drugs also shortened the smothering time, suggesting that drugs had a similar effect as alcohol. Unfortunately, the participants were not asked to specify what kind of drugs had been used. Therefore, no conclusions could be drawn about any differences in effects between stimulants and

depressants. Furthermore, no conclusions about interaction effects between alcohol and drugs could be drawn.

Larger participants required less time to complete the smothering, whereas no significant effect of weight was found. This might be because it was easier for larger participants, due to their larger reach, to position their center of mass above the dummy head and use their weight more effectively. Placing the body weight as much over the head as possible proved most effective in applying high smothering forces. Furthermore, leaning on two feet or two knees provided higher maximum forces than when having one knee on the bed while keeping one foot next to the bed. This possibly was because of improved balance and center of mass placement, but could also be related to the fact that some participants put the leg next to the bed backwards or even off the floor when leaning with a knee on the bed. The latter would create a counter moment, reducing the body weight on the head.

Although care was taken to keep identical space on both sides of the bed, participants tended to avoid the right side of the bed, possibly because that is where the measurement computer and supervisor were. Although the available space left few options to

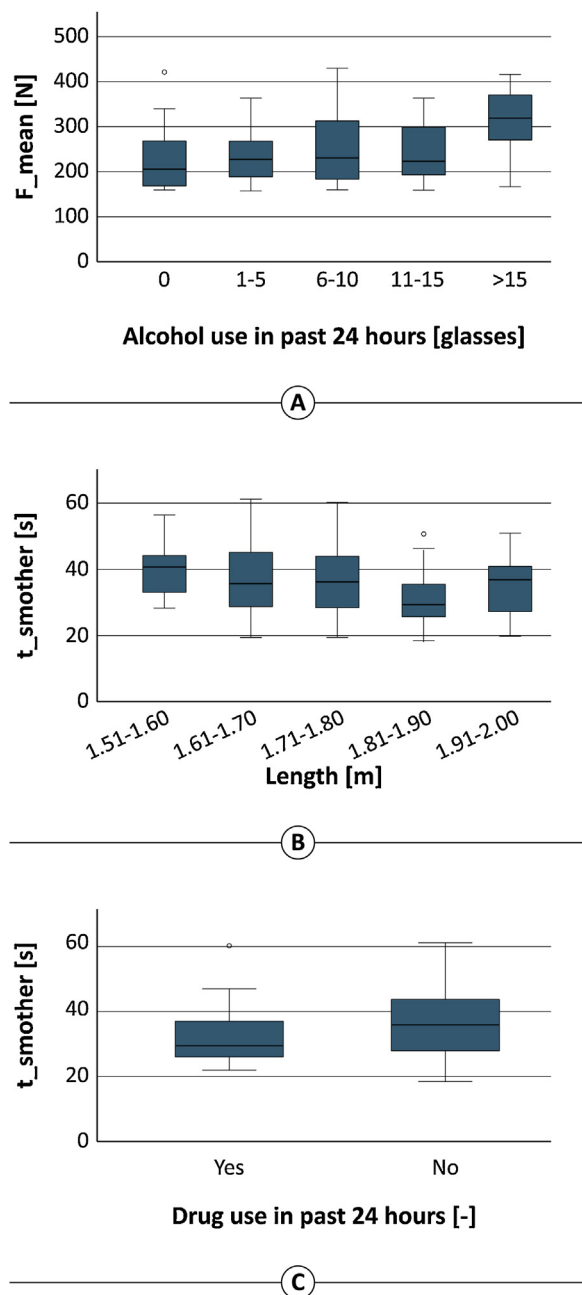


Fig. 6. Box plots for factors queried in the questionnaire that had a significant effect on the smothering time or mean smothering force. Middle lines indicate the medians, the boxes span the 25th to 75th percentiles, the whiskers indicate the range of the data and circles indicate outliers. **A)** Alcohol use versus mean smothering force. **B)** Length versus smothering time. **C)** Drug use versus smothering time.

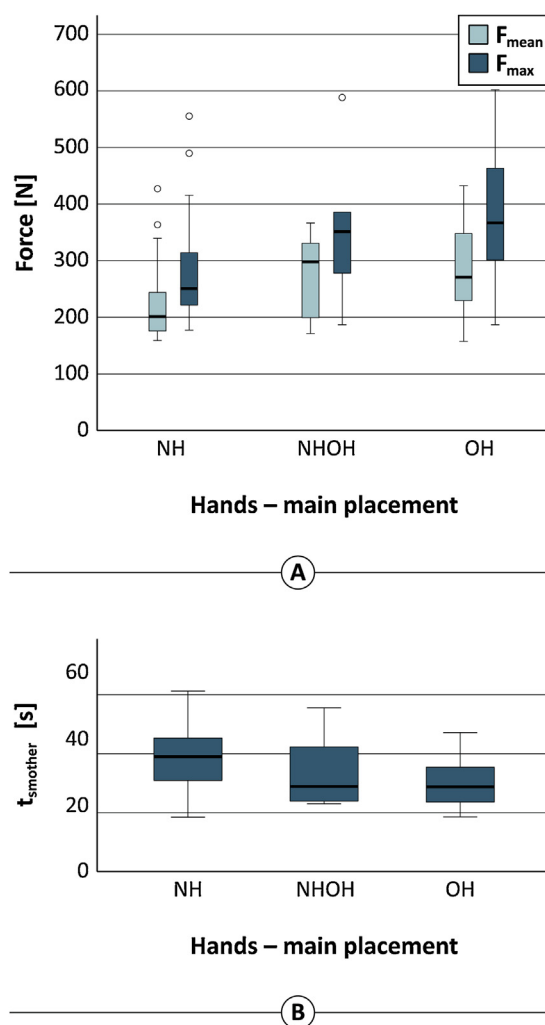


Fig. 7. Box plots for the MO characteristic 'Hands - main placement' showing the significant effect of the subjects' hand placement mainly on the dummy head during smothering on **A)** mean and maximum smothering forces and **B)** smothering time (t_{smother}). Middle lines indicate the medians, the boxes span the 25th to 75th percentiles, the whiskers indicate the range of the data and circles indicate outliers. Hands placement variants are indicated by NH (both hands next to the dummy head), NHOH (one hand next to and one hand on the dummy head) and OH (both hands on the dummy head).

not have the measurement computer in the same room as the bed in future experiments, it would be advisable to put any equipment in line with the bed to avoid participants from being biased. Furthermore, the view from the single camera was blocked in several tests, leading to exclusion of these data. Adding extra cameras for different viewpoints would have improved the view on the experiments and would have made establishing the MO much easier. However, in the current experiment full and easy-to-achieve anonymity of the subjects was preferred over having better video recordings. Only one participant tried to apply smothering by placing his arm around the dummy head and pressing the pillow on the dummy face (burking). Although this is known to be an effective smothering MO, the participant was asked to remove his arm from behind the head, because the construction of the test setup did not allow measuring any forces if the head wasn't pushed upon. Because no other subjects attempted this MO, this didn't affect the outcome of the experiment.

The applied smothering threshold of 150 N was based on tests on a single, healthy, 1.74 m tall, 70 kg weight, male subject. This threshold was therefore rather arbitrary and may differ among victims and may be particularly different for elderly, infants and ill, allergic or asthmatic victims. For the experiment, the smothering scenario was designed as realistic as was possible within the boundaries of the situation: short duration, minimal chance of adverse psychological effects, fully anonymous. In a real life situation a victim is more likely to struggle for survival, while the dummy obviously provided no resistance.

The actual time required for smothering a person until unconsciousness is about 5 min [8–10], although bradycardia can occur after 30 s and ECG flattening starts at about 90 s, or sooner if much oxygen is consumed by heavily fighting back [12]. In the tests only up to 45 s of smothering was required, and usually less (Fig. 8). Yet, this did already deliver valuable results: the variation of MOs applied during smothering, the force variations and their relations to participant characteristics. Nonetheless, if longer smother times would have been required or if the dummy was somehow made to fight back, more participants may eventually not have been able to complete the smothering due to fatigue or lack of strength, more MOs might have been alternated within a single participant's attempt, and some yet undiscovered smothering MOs might have been revealed. Of course the lack of a struggling victim does make the current results unlikely to fully translate to cases with healthy, conscious victims. However, the majority of smothering victims are known to be too young, old or weak to resist [12–14]. Yet, even in resistive victims the currently found MOs would still be expected to occur, possibly amongst others. To check whether longer smothering times were primarily caused by lower forces or by increased duration of the moments that smothering forces were below the threshold, the

smothering efficiency $Eff_{smother}$ was calculated as $t_{smother}/t_{valid}$. However, none of the MOs or questionnaire variables showed to have a statistical effect on $Eff_{smother}$. This may suggest that longer smothering times were in fact caused by the exertion of less force. Another explanation might be that the requested smothering times were too short to allow finding any exhaustion effects, even though several subjects could already barely keep up the required force. Because the efficiency variations were very small, no further analyses on interaction effects were done.

There were rather large differences in group sizes in sub-groups of participants of different age, height, weight, drug use, alcohol use and preferred hand. More equal group sizes would have allowed for more robust statistical testing and might have revealed effects that were now left undiscovered. The questionnaire would have provided more complete information if the type of drugs used had been asked for (depressants versus stimulants). Furthermore, information about disabilities or diseases possibly affecting participants' strength or stamina could have been valuable for more detailed interpretation of the data.

Different smothering MOs may leave different hand and finger marks on different locations on the pillowcase. Combining the obtained data with information about the location of hand and finger marks left on a pillowcase [6] may help to better interpret traces left on a pillowcase that has possibly been used for smothering.

5. Conclusions

A total of 181 music festival visitors used a pillow for simulated suffocation of a victim, with the data of 152 being included for analysis. This provided detailed knowledge about the MOs and forces applied by participants of various builds and ages during smothering. Furthermore, the results suggested that drug and alcohol intake had stimulating effects on the fierceness of smothering. From the video observation data it was established which MOs were used and which participant postures seemingly helped to speed up the smothering. After linking the current results to the location of hand and finger marks on the pillowcases in the future, the combined information might help forensic investigators to know more precisely where to look for traces, to establish offender profiles, to link similar cases, to check the stories of suspects and to help establish the chain of events in smothering cases, particularly in cases where victims could not fight back.

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Ethics approval

This study was approved by the Delft University of Technology Human Research Ethics Committee (study number 46).

Consent to participate

All participants signed an informed consent form for their anonymous participation.

Consent for publication

All participants signed an informed consent form for the publication of the anonymous data gathered during the experiments.

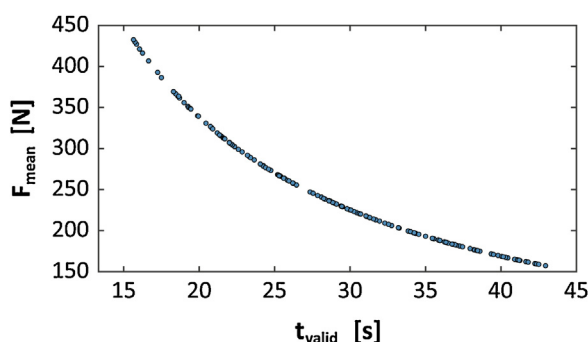


Fig. 8. Smothering time above the smothering threshold (t_{valid}) versus mean smothering force exerted by subjects on the dummy (F_{mean}). Each dot represents a subject.

Availability of data and material

The full dataset, informed consent and debriefing forms, and the used custom data acquisition software are available at <http://doi.org/10.4121/uuid:36ca19b5-18a7-41be-9387-dc9b3127de61>.

Code availability

Acquisition software has been published together with the dataset.

CRedit authorship contribution statement

Danique Prinsen: Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Arjan van Dijke:** Methodology, Software, Resources, Project administration, Investigation, Writing - review & editing. **Tim Horeman-Franse:** Methodology, Resources, Investigation, Writing - review & editing. **Nick van de Berg:** Methodology, Software, Investigation, Writing - review & editing. **Arjo J. Loeve:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition, Supervision.

Declaration of Competing Interest

Not applicable.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at [doi:https://doi.org/10.1016/j.forsciint.2020.110521](https://doi.org/10.1016/j.forsciint.2020.110521).

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