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Determination of relevant sampling locations for burglary investigations

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ABSTRACT

Residential burglaries often go unsolved, as collected DNA traces and fingermarks frequently originate from residents rather than the offender. It is therefore important to know how to target sampling locations that specifically relate to the burglary event. However, data that aid in assessing the likelihood of a burglar touching certain surfaces, and, consequently leaving trace evidence, is unavailable. Instead, forensic examiners rely primarily on their personal experience and expertise to determine where burglary-related traces are most likely to be found.

The current study aims to identify specific areas that are contacted during different types of interactions with points of entry. An experiment was conducted at a Dutch music festival, where participants simulated both a legitimate and burglary scenario. Using paint, the points of contact between the participants' hands and the experimental set-up were recorded. The contact locations of all participants were combined using heatmaps to reveal the patterns of contact. We found that different burglary methods lead to distinct contact patterns, indicating specific areas where traces are most likely to be deposited. Our findings can support forensic examiners in making evidence-based decisions during search strategies in burglary investigations.

1. Introduction

There is an urgent need to prevent and solve burglary cases. With 22,761 registered incidents in the Netherlands in 2023 [1], residential burglaries are considered high volume crimes. Apart from being common, burglaries have a significant impact, as being a victim of a burglary can cause various types of psychological distress and may potentially be a traumatic experience [2]. While the annual number of residential burglaries in the Netherlands has consistently decreased, the relative clearance rate for these cases has remained unchanged over the last decade (around 10 %) [1]. Similarly low clearance rates have been observed internationally [3,4].

The persistent (un)solvability of residential burglary cases may partly be due to forensic ineffectiveness. In the absence of witness statements or camera recordings, the identification of potential burglars primarily relies on forensic trace evidence, such as DNA traces and fingermarks [5]. Despite the unprecedented capability of modern forensic methods and the continuous development of forensic databases [6–9], the contribution of forensic evidence in volume crime leaves much to be desired. In a study of over 800 residential burglaries, Antrobus and Pilotto [5] found that forensic evidence directly contributed to the outcome in only less than half of all solved cases [5]. Furthermore, Wüllenweber and Giles [10] reported a negative correlation between the presence of fingermarks and forensic effectiveness (which they defined as the contribution of forensic evidence to reach a criminal charge). As this was particularly the case for residential burglaries, the authors argued that this may be due to the common presence of fingermarks originating from residents [10].

The abundance of fingermarks within households and the high likelihood that forensic evidence originates from residents indeed complicates trace selection. With regard to DNA traces, the overwhelming presence of prevalent and background trace material originating from residents can be responsible for forensic ineffectiveness in volume crimes. By structurally collecting reference material from residents during burglary investigations, Tièche et al. [11] reported that the vast majority (75 %) of trace contributors were the residents themselves

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[11]. Furthermore, the presence of background DNA can hinder the detection of DNA that is foreign to the environment, such as DNA originating from an offender, who is often assumed to be the last person to have touched a certain surface [12,13].

Another reason for forensic ineffectiveness could be that traces originating from an offender are simply hard to find. Burglary-related DNA traces and fingermarks may be rare, if not absent, as forensic awareness amongst burglars leads to strategies for avoiding detection, such as wearing gloves or wiping away fingermarks [14]. Alternatively, it could be that burglars do in fact leave traces behind, but that these are overlooked by forensic examiners. Simply collecting and analyzing more trace evidence to increase the chances of success will however not be the solution, as this requires additional resources and – more importantly – does not necessarily lead to more identifications [5,15]. Instead, improved knowledge of which sampling locations are most likely to contain burglary-related traces is necessary.

In order to determine relevant sampling locations, we need to consider that the likelihood of recovering trace material (DNA or fingermarks) depends on two different probabilities: (1) the probability of a person touching a specific area, and (2) the probability of trace transfer, persistence and recovery (TPR) when that area is touched. While experimental data on burglaries can be used to inform the second probability [16–20], this does not help to actively guide the search strategy. It is instead the first probability that is of most relevance here, which is best assessed using knowledge on offender behavior. Although criminological studies have given insights into the decision-making of offenders during the act [21–23], they do not provide any details on the specific locations where samples need to be collected. For these reasons, current guidelines on crime scene investigation are limited, and forensic examiners are left to mostly rely on their own experience and expertise, using approaches that differ from one examiner to the next [24].

The current study aims to determine the specific contact locations involved in various types of interactions with points of entry. We focus on the points of entry because these are most commonly used as the starting point for forensic examiners' search strategies, based on their experience, and has also been shown to be the most promising area for finding offenders' DNA [11]. An experiment was carried out at the Dutch music festival *Lowlands*, where participants from the general public simulated both daily and burglary-related activities involving doors and windows. The use of simulation data to inform relevant sampling locations and trace interpretation has already proven valuable in studies focusing on violent crime and sexual assault [25–27]. These studies also serve as inspiration for the current experimental set-up. To visualize the points of contact with the palmar surface of the hand and fingers, paint was applied on the inside of participants' hands. By transferring paint from their hands to the experimental set-up while performing the activities, the contacted areas were revealed. Combined data from all participants were visualized using heatmaps to obtain the general patterns of contact within each scenario. These visualizations indicate where actual DNA traces and fingermarks can potentially be found within a real-life burglary investigation.

2. Materials and methods

This study was facilitated by *Lowlands Science 2023*: a citizen science program that is part of the annual *Lowlands* music festival (Biddinghuizen, The Netherlands). Through this program, visitors can participate in experiments, allowing researchers to gather a large number of participants from the general public during the three-day festival.

2.1. Participants

A total of 201 volunteers participated anonymously in the experiment. Visitors of the festival were allowed to participate if they were 16 years of age or above. Only visitors who were visibly and significantly under the influence of alcohol and/or drugs were excluded from participating. No other restrictions were in place to prevent certain visitors from participating. A written and signed informed consent was obtained from all participants, and the study was conducted with approval from the Amsterdam University of Applied Sciences research ethics review committee (request ID HVA-111).

2.2. Experimental procedure

Throughout the experiment, a personal instructor guided the participants and monitored the personal wellness and safety of the participants. To begin, participants were asked to fill out an online questionnaire using their smartphone. This questionnaire recorded general demographics, their use of alcohol and/or drugs in the last 12 h and their familiarity with the burglary techniques tested in the experiment.

Next, all participants carried out multiple activities that were part of either a legitimate or burglary scenario (Fig. 1). The first scenario consisted of three daily activities. Participants were asked to (1) deliver an envelope through the mail slot, (2) open the door with the house key and (3) open and close the window. To ensure that all participants opened the window all the way and to a similar extent, the tool required for the second scenario – either a plastic loiding card (21 × 10 cm, 0.35 mm thickness; Secupro Nederland, Haarlem, NL) or a bent wire hanger (Home&Garden, Almere, NL) – was placed behind the window. These tools correspond to two burglary techniques that are common in the Netherlands, relatively simple to perform for laymen and do not damage the door or its lock, allowing multiple participants to perform the activity. The two methods are only applicable when a door is closed, but not properly locked with its key. The first method is *loiding*, also known as *carding*; a technique in which the plastic card (the loid, referring to celluloid) is inserted between the door and the door frame and applies pressure to the spring latch. By pushing the latch back into the closing mechanism, the door will open. The second method is the *letterbox burglary*, using the wire hanger. By inserting a bent wire hanger through the mail slot, the hook end can 'fish' for the interior door handle to open the door. After retrieving one of the tools, participants received new instructions for the burglary scenario.

The burglary scenario simulated a break in (attempt) and escape through a window. Participants were randomly assigned one of the methods – loiding or the letterbox burglary – and only received a brief explanation. No demonstration or detailed instructions on how to place the plastic card or hanger were given. To ensure that participants only focused on the task at hand and not on their trace deposition, a stress element was added in the form of a three minute time limit. The time limit further helped participants experience the stress a burglar might feel during an actual burglary. In case participants were not able to open the door in time, they were asked to stop but were allowed to complete the experiment by opening the window and climbing through it.

To visualize the points of contact, participants applied a water-based paint (SES Creative, Enschede, NL) to their hands prior to the experiment. Throughout the experiment, the paint was reapplied to participants' hands whenever the instructor observed the participants' hands to be dry. This ensured that enough paint could be transferred from the hands to the experimental set-up for all activities. After completion, the paint deposited on the experimental set-up was recorded by flash photography using a Nikon D700 camera with an aperture of f/5.6, 1/80 s shutter speed and ISO 400 film speed. Photography followed the crime scene procedure, meaning that overview images of the areas of interest (doors or windows) were taken, followed by detailed images of specific subareas (e.g. doorknob, letterbox, window handle) where applicable. Following photography, the experimental set-up was cleaned using a damp cloth and all-purpose cleaner, and prepared for the next participant.

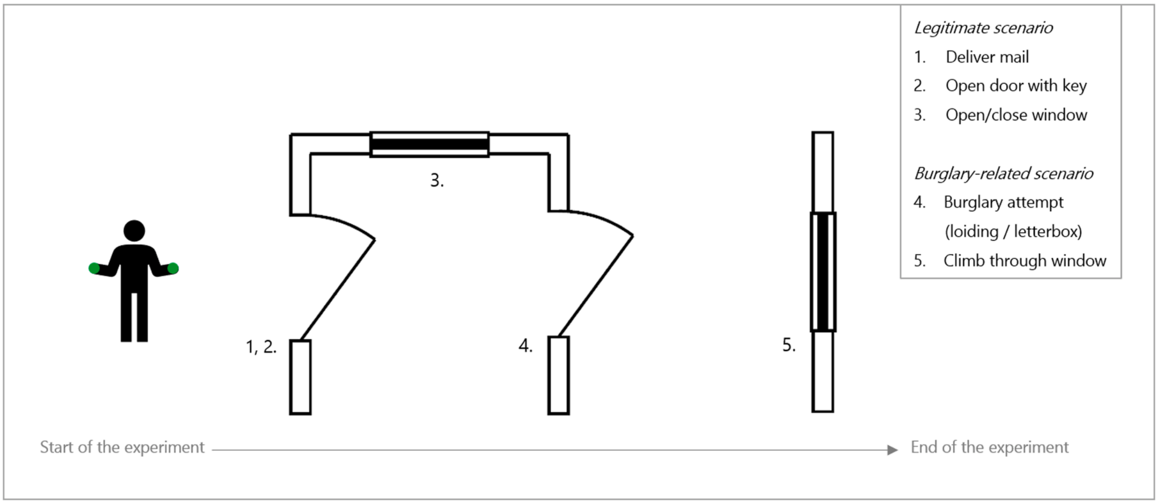

Fig. 1. Overview of the experimental set-up with instructions for participants. After applying paint to the participants' hands, a legitimate scenario containing daily activities was simulated first, followed by a burglary scenario containing one of the two burglary methods. Paint was reapplied in between activities whenever necessary.

2.3. Experimental set-up

An experimental set-up was created to simulate the points of entry of a residence. A construction consisting of wood and wood paneling was built, in which doors and windows were installed. To mimic a common Dutch residential front door, hollow honeycomb core doors (210 × 80 cm) were adapted by inserting a mail slot and lock and exchanging the exterior door handle for a doorknob. As it was expected that most participants would have no prior burglary experience, the doors were modified to slightly lower the difficulty of the burglary methods. Door frames were slightly sanded down to allow plastic cards to be inserted more easily. The interior door handle was covered in paper tape and a tie-wrap was fixed at the end to avoid the wire hanger sliding off too easily. While these adaptations simplify the burglary attempt, it was expected that they would not affect the locations that are touched and thus, the trace deposition.

Tilt-and-turn windows (80 × 80 cm) with vinyl frames were placed at 80 cm above ground. To prevent reflections using flash photography, the window panes were covered in a plastic privacy foil (Simple Fix Nederland, Hendrik-Ido-Ambacht, NL). All doors and windows were right-handed, meaning the hinges were located on the right side and they opened inwards.

To aid interpretation of the data, measurement tapes were stuck along door and window frames as well as markings at every 50 cm in height. For a detailed illustration of the construction including measurements and corresponding on-site photo, see supplementary Figures

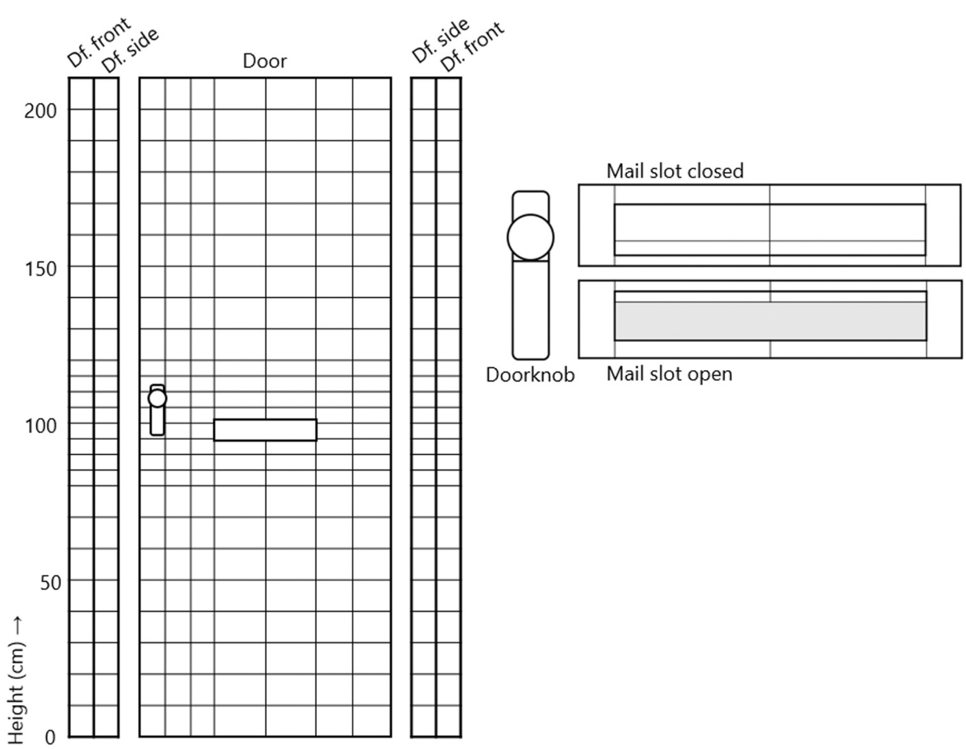

Fig. 2. Grid designs to determine contact locations on the door. Doorframes (Df.) are adjacent to the door on either side. On the right, a detailed grid of the door hardware can be seen with light grey indicating the gap in the opened mail slot.

S1 and S2.

2.4. Data processing

The photographic data were reviewed prior to further analysis to assess their suitability. Images that did not include the measurement tapes or contained unreadable measurement tapes were excluded as these obstructed the precise localization of the paint deposits. To determine the contact locations on the doors and windows, as indicated by the deposited paint, photographic data were preprocessed using the open-source software GNU Image Manipulation Program (GIMP, version 2.10).

Using GIMP, all images were aligned with a pre-determined grid design, showing the various locations to be assessed for the presence of paint. A grid design was created showing the door and adjacent sides of the doorframe with both the front view and the inner sides of the doorframe (Fig. 2). The top side of the doorframe has been omitted due to an expected lack of contact with this area, considering its height. Furthermore, a more detailed overview of the door hardware was created to assess specific sublocations on the doorknob and underlying doorplate, as well as the mail slot in closed and open condition, showing the underside of the rim. For clarification, we refer to supplementary Figure S3 for an additional image of the mail slot with grid overlay.

Regarding the windows, three separate grid designs were created: one for the interior side, facing the inside of the home; one for the interior side in opened position, showing the inner edges of the frame; and one for the exterior side, facing the outside of the home (Fig. 3). It should be noted that as the window sash (the movable part containing the window pane) and the underlying window frame partly overlap all around (width ± 1 cm), the outer edges of the window sash are not visible in the exterior side representation.

Similar to the studies of Ramos et al. [25] and Zuidberg et al. [27], the presence or absence of paint was manually recorded for each location within the grid using a binary scoring method (i.e. '0' if no paint was observed and '1' if paint was observed). Paint deposits were scored by two raters, one for the doors and one for the windows. To test the reliability of the subjective scoring method, the two raters repeated the scoring for a random 10 % of participants to assess the intra-rater variability. Furthermore, a third rater scored an additional 10 % of both doors and windows to assess the inter-rater variability.

2.5. Data analysis

After recording all contact locations for each participant, the collected data of all participants were combined to determine the frequency with which each location had been contacted. Here, heatmapping is used to visually represent the frequency data values through a color gradient. These heatmaps reflect the spatial distribution of contact points using the above-mentioned grid designs, with darker colors indicating higher frequencies, to show the general patterns of contact for each scenario.

To determine whether the burglary activities result in a different number of contact locations compared to the legitimate activities, statistical testing was carried out using R (v4.3.1) [28] and Rstudio (v2024.09.1 + 394) [29]. As each participant has carried out the legitimate scenario and one of the burglary scenarios, a paired Wilcoxon signed rank test was used to test between the two scenarios. To test between the two burglary methods, the unpaired Wilcoxon rank sum test was used, as the two methods were carried out by two different groups of participants. Both tests were based on a significance level of 0.05.

3. Results

3.1. Participants

In total, 201 participants completed the experiment. Within this group, ages ranged from 19 to 54 years old (M = 28,3, SD = 6.5), with a near equal distribution between male (51 %) and female (49 %) participants. This makes our test group representative for the demographic of burglars with regard to age, however the proportion of female to male participants is much higher compared to the actual burglar population [30,31].

All 201 participants performed the legitimate scenario and one of the two break-in methods (loiding or a letterbox burglary) within the burglary scenario. 93 participants simulated a burglary through loiding, of which 11 % had experience with the technique (meaning they carried out the method before) and an additional 39 % had heard of it. The other 108 participants simulated a letterbox burglary, of which 11 % had experience with the technique and an additional 40 % had heard of it. All 201 participants finished the scenario by climbing out of the window.

As the experiment took place at a music festival location, alcohol and drug use was recorded using the questionnaire. The vast majority of participants (77 %) self-reported to have consumed alcohol within the last 12 h; with most of these (74 %) having consumed up to five alcoholic beverages. 17 % of participants reported drug use within the last 12 h, with the most frequent drugs being MDMA (19 participants) and cannabis (13 participants). Out of all participants, 13 % reported the combined use of alcohol and drugs. As participants that were notably under the influence of any substance were excluded from participation, we expect these numbers to not be of much influence to the results of the experiment. Only 6 % of alcohol consumers further reported feeling

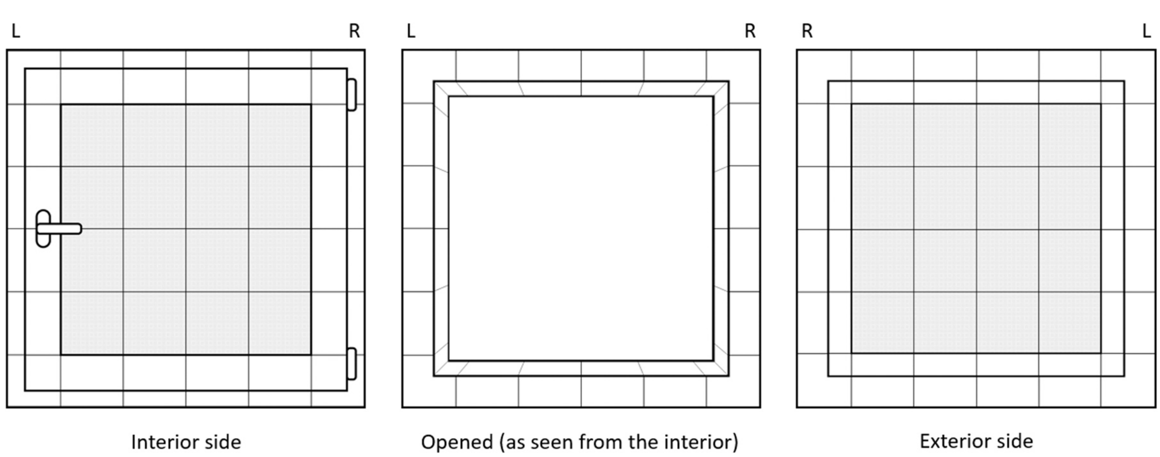

Fig. 3. Grid designs to determine contact locations on the window frame. Naturally, the exterior side is presented as a mirror image of the interior view. The glass window pane is indicated in light grey.

tipsy, with the remaining 94 % feeling either sober or disinhibited.

3.2. Quality assessment

As mentioned before, the suitability of the photos taken was reviewed prior to analysis. For the doors, this led to the inclusion of 197 (98 % of total) participants for the legitimate scenario; 93 (100 %) participants for the loiding scenario; and 107 (99 %) participants for the letterbox burglary scenario. Within these groups of participants, additional images were taken of the opened mail slot to assess the presence of paint underneath the rim in 154 (out of 197) cases for the legitimate scenario and 77 (out of 107) cases for the letterbox scenario. No photos of the opened mail slot were obtained for the loiding scenario, as the mail slot logically needs not to be opened for this activity. For the window frames, a higher number of photos was excluded as these were not sharp enough to reliably analyze the paint deposits, likely due to glare from the window pane. Review of the photographic data in this set led to the inclusion of 173 (86 %) participants for the legitimate scenario and 163 (81 %) for the burglary scenario. It should be noted that for the burglary scenario (climbing out), only participants for whom a full set of images was available were used for further analysis. Here, a full set consists of an interior side, one opened and one closed, and an exterior side of the window frame. This was done to aid correct interpretation of the data as a full set represents the complete distribution of contact locations. For a full overview of the included data, see Table 1.

3.3. Scoring consistency

To determine the inter- and intra-rater reliability, the percent agreement between two raters was calculated based on all cells that were denoted in the grids. Using the data obtained from the doors, the percent agreement representing the intra-rater reliability was determined to be 99.7 %. The percent agreement representing the inter-rater reliability was determined to be 99.3 %. Using the data obtained from the windows, comparable results were found. In this case, the percent agreement representing the intra-rater reliability was determined to be 98.9 %, whereas the percent agreement representing the inter-rater reliability was determined to be 98.5 %. Based on these numbers, we consider the used scoring method to be reliable, as the absolute percentage agreement values are well above the acceptable threshold of 80 %, as proposed in [32].

3.4. Areas of contact

3.4.1. Doors

Visual determination of the contact locations per participant per scenario (as indicated by the cells in the grid) showed a low number of touched locations (including door hardware) for the legitimate activities tested ($M = 5.05$, $SD = 2.75$). This appears to be much lower compared to the burglary scenarios for both the loiding scenario ($M = 25.81$, $SD = 9.05$) and the letterbox burglary ($M = 12.64$, $SD = 6.94$). Statistical testing was carried out to determine whether participants touched significantly more locations during the burglary scenario and whether the two burglary methods differed significantly from each other. Paired statistical testing using the Wilcoxon signed-rank test indicated that the differences between the legitimate scenario and each of the burglary methods were statistically significant ($p < 0.05$). Unpaired statistical testing using the Wilcoxon rank-sum test also showed a significant difference in the number of touched locations between the two different burglary methods ($p < 0.05$).

Table 1
Included data after photo review.

Entry point	Scenario	# of participants	% of total
Windows	Legitimate	173	86 %
	Burglary (full sets)	163	81 %
Doors	Legitimate	197	98 %
	Loiding	93	100 %
	Letterbox	107	99 %
Additional images			
Opened mail slot	Legitimate	154	78 %
	Letterbox	77	72 %

By combining the distribution of the contact locations for all participants, the data have been visualized in heatmaps per scenario (Fig. 4). Color intensity reflects the proportion of participants who touched a certain location, with 1 indicating that all participants deposited paint and 0 indicating that none of the participants deposited paint on the given location.

In the legitimate scenario, contact locations mostly accumulate on the door hardware with the highest proportions of over 0.8 and 0.9 on the doorknob and mail slot respectively. Surrounding the door hardware, a few contact areas are also found on the surface of the door itself and on the doorframe. Contact in these areas can be found mostly on the doorframe between 100 and 130 cm in height, near the doorknob. Yet these proportions remain low, with a maximum of 0.1, meaning that a maximum of 10 % of participants touched these locations.

In the loiding scenario with the plastic card, a frequent contact area is observed around and above the doorknob, with proportions reaching up to 0.97. As the loiding card needs to be inserted in this area to push back the closing mechanism of the door, such high proportions were expected. Proportions higher than 0.5 (indicating a likelihood of 50 % or greater that participants touched a location) are found along the doorframe and edge of the door between 95 and 140 cm from the ground. Any areas higher or lower than these limits show a rapid decrease in contact proportions.

Finally, in the letterbox burglary with the wire hanger, the opposite pattern is observed. As expected, the highest number of contacts can be found on the mail slot itself, with all participants having touched it (a contact proportion of 1). This was expected since the mail slot must be opened to carry out the activity. Furthermore, a wide distribution of low contact proportions can be seen on the door surface, with an accumulation of higher proportions right below the mail slot. Specifically, the first 10 cm below the mail slot appears to be the most promising area to search for traces, with proportions ranging from 0.21 up to 0.83 in the left corner directly below the mail slot. Further down, proportions drop to around 0.1 and below. Anecdotally, paint has also frequently been observed inside the mail slot itself, and beneath the mail slot on the interior side of the door. These locations have not specifically been recorded for this study, but may be of interest when targeting the doors for traces of burglars.

As can be seen in the overviews of Fig. 4, contact has been made with the door hardware in various degrees in all three scenarios. For example, the mail slot shows high proportions (> 0.9) for both the legitimate scenario and letterbox burglary. On this general level, these would thus appear to be similar. However, by dividing the mail slot in twelve specific sublocations (two of which underneath the rim) different distributions of touched areas are revealed. For legitimate activities, most contact is found below and on the rim (both on top and underneath). For the letterbox burglary, these findings are amplified and more high contact areas are also found on the other areas of the mail slot. Indeed, while the mail slot was touched in both scenarios, participants contacted more sublocations on the mail slot during the letterbox burglary ($M = 6.75$, $SD = 2.05$), compared to delivering mail as part of the legitimate scenario ($M = 2.96$, $SD = 1.72$).

As contact locations related to burglar activity may also contain traces left behind by residents or other legitimate users, it is relevant to know to what extent the contact locations overlap between the two scenarios. As shown in Fig. 5, the contact area corresponding to the two burglary methods almost completely encompasses the contact area corresponding to the legitimate scenario and extends far beyond that. As such, many of the contact locations have only been touched during the burglary scenario. However, as can be seen in the individual heatmaps,

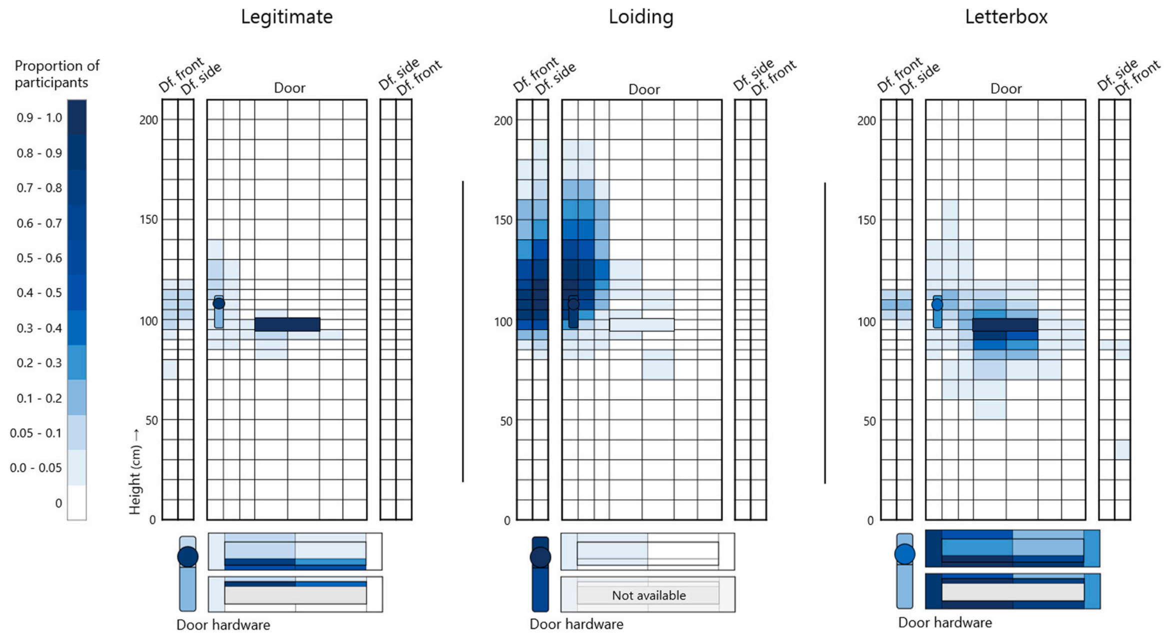

Fig. 4. Heatmap comparison of the doors with adjacent doorframes (Df.) and door hardware. Overview of the legitimate scenario (delivering mail and using the house key) and the two burglary methods (loiding and letterbox burglary). A color gradient shows the proportion of participants who touched each location, with darker colors indicating higher proportions.

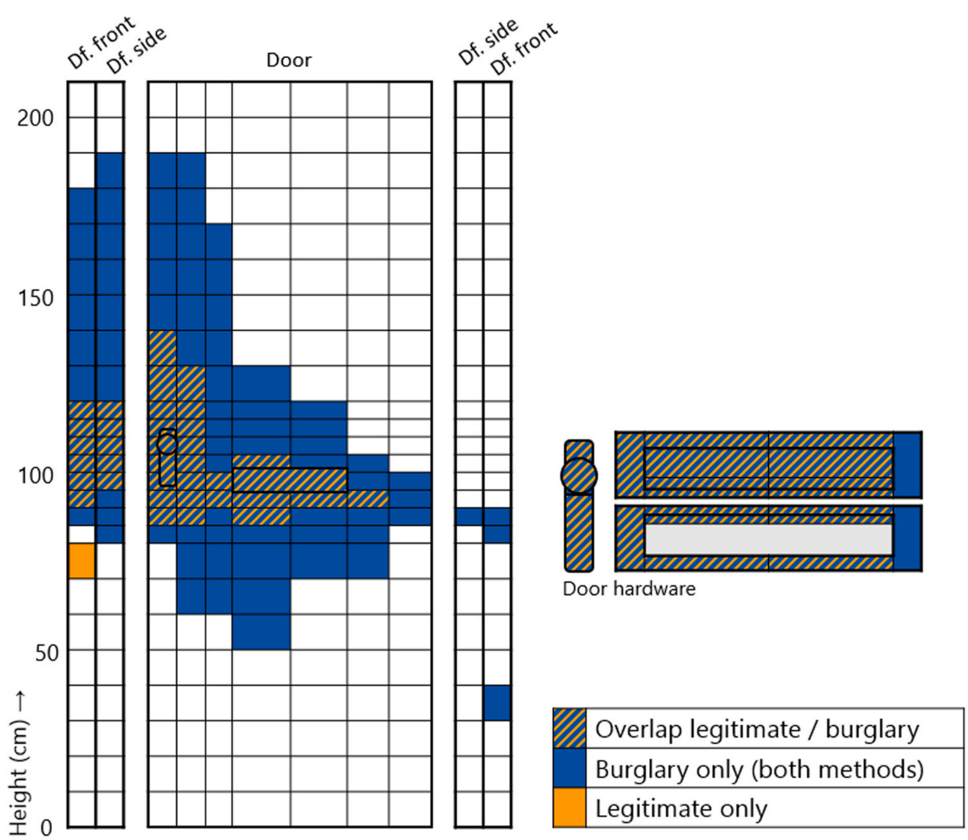

Fig. 5. Overlap between legitimate activity and the two burglary methods.

the contact proportions for burglary-related activity within these ‘burglary-only’ areas can be much lower compared to the areas showing overlap. Furthermore, overlapping areas do not equally represent the legitimate and the burglary scenario, as the likelihood of contact within these areas can still differ greatly between the two. Therefore, the areas of overlap need to be considered with the difference in contact proportion in mind.

3.4.2. *Windows*

As the inside and the exterior side of the window frame have not been recorded following the legitimate activity, the comparison with the burglary scenario can only be conducted using the interior side of the window frame. Regarding the number of locations from which paint was recovered, the difference between the legitimate scenario and the burglary scenario is a lot smaller for the windows than for the doors. Using the Wilcoxon Signed Rank test, the average number of contact locations on the interior side of the window frame was compared between the legitimate and burglary scenario. It appeared that the number of contact locations for the legitimate scenario was again significantly lower than for the burglary scenario ($M = 2.18$, $SD = 1.38$ vs. $M = 3.42$, $SD = 1.94$; $p < 0.05$).

Comparing the contact distributions between the two types of activities, similarly high proportions can be found on and around the window handle in both heatmaps (Fig. 6). Logically, making use of the window handle is a requirement to open the window, so these high proportions are not surprising. Aside from high levels of contact directly above and below the window handle on the window sash (containing the window pane), few contact locations can be found within the legitimate scenario. The areas of contact within the burglary scenario are shown to be more diverse with different locations being touched by the participants. Aside from the contact with the window sash, more contact is also observed on the window frame surrounding and underneath the sash: 38 % of participants touched the window frame during the burglary scenario, as opposed to only 1 % during the legitimate scenario. Yet, the levels of contact on the window frame for the burglary scenario are generally low as contact areas appear to be spread out. In both scenarios, contact with the hinge side of the window appears to be rare.

When looking more closely at the burglary scenario where the window was used to climb through, the inner parts of the window frame as well as its exterior side become relevant (Fig. 7). Judging the three heatmaps as a whole, no strong distinct patterns are visible. Here again, the heatmaps generally show a wide distribution of contacted areas. The frequencies with which the inner side and exterior side of the window frame are touched are relatively low, with the highest values reaching just above 0.2. These areas can be found on the sides and bottom ledge of the window frame, possibly indicating that participants placed their hands on one or both sides to push themselves through, or on the bottom ledge to lift themselves over the window frame.

Similar to the data obtained from the doors, overlapping areas on the window provide information on where traces from both burglary-related and legitimate activity may be expected. Based on the interior side of the window frame, overlap is mostly found on the window sash on the side of the handle and almost completely corresponds to the areas found within the legitimate scenario (Fig. 8). Only two locations have only been touched during the legitimate activity, whereas a vast majority of locations have been touched during the burglary activity.

3.5. Trace interpretation

Whereas the heatmaps presented above provide relevant information to guide search strategies at the crime scene, the data may also be useful for trace interpretation. Once a DNA profile is obtained or a fingermark is recovered from a particular location, it would be valuable to know whether this location is more frequently touched in the burglary scenario or in the legitimate scenario. This information, combined with knowledge on trace transfer and background levels on points of entry, may be used to determine whether traces found at a given location are more likely the result of a burglary or a legitimate act.

Whether the burglary scenarios lead to higher (or lower) contact proportions at particular locations can be easily visualized by subtracting the contact proportions for the legitimate scenario from those for the burglary scenarios. As stated earlier, the contact proportions range from 0 (none of the participants made contact with the location) to 1 (all participants made contact with the location). Hence, if these values are subtracted, the difference score ranges from $+1$ (indicating that all participants touched the location during the burglary scenario, whereas none of the participants touched it during the legitimate scenario), to -1 (indicating that none of the participants touched the location during the burglary scenario, whereas all participants touched it during the legitimate scenario).

By visualizing those difference scores, it becomes clear which specific locations are touched more frequently during one of the scenarios, indicating that the probability of contact is higher for one of the scenarios compared to the other (Figs. 9 and 10). It also reveals locations that are touched in roughly equal proportions in both scenarios, leading to a difference score close to zero. However, locations that have not been touched during one scenario and only rarely during the other, will also provide a difference score that is close to zero. To differentiate between these instances, it is important to consider that the difference scores (Figs. 9 and 10) and the contact proportions from the heatmaps (Figs. 4 and 6) complement each other and should be used in conjunction. After all, locations that are rarely touched or have equally high contact

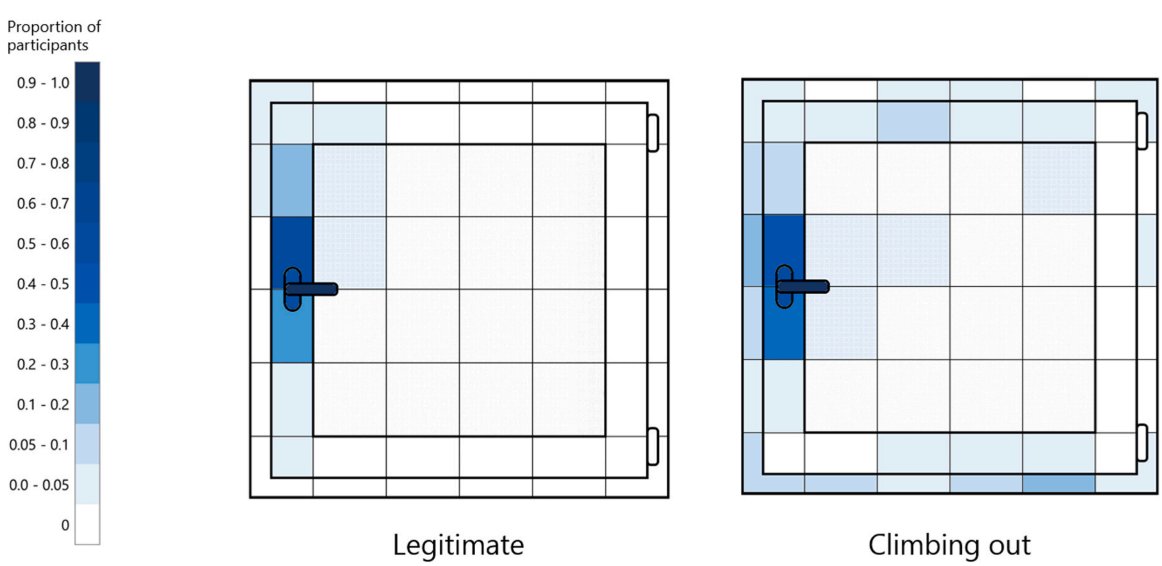

Fig. 6. Heatmap comparison of the interior side of the window frame, showing the legitimate scenario (opening the window) and burglary scenario (climbing out). A color gradient represents the proportion of participants who touched each location, with darker colors indicating higher proportions and thus levels of contact.

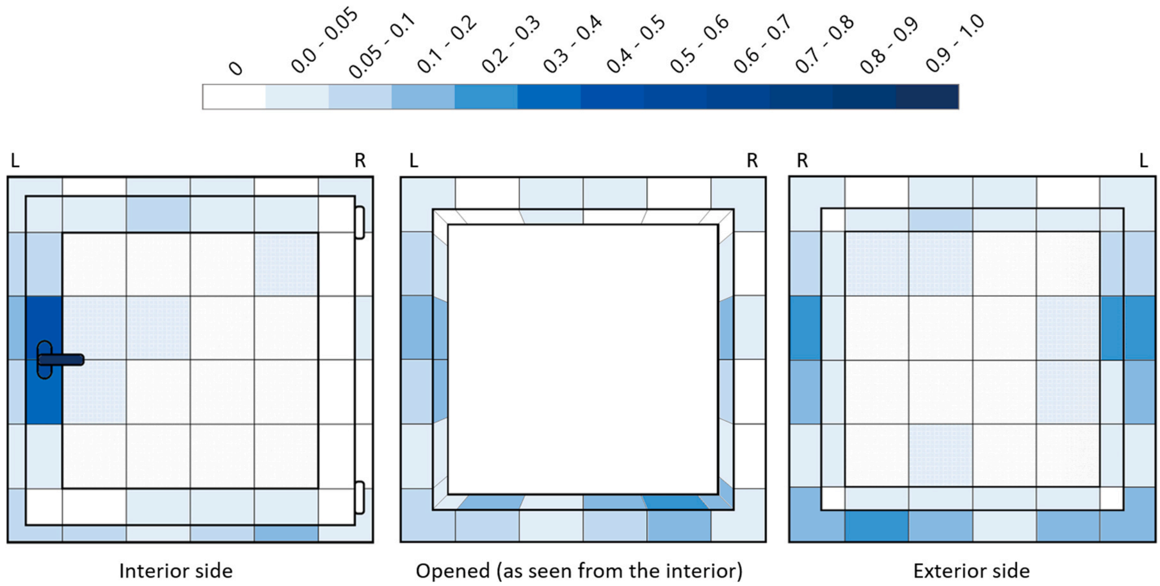

Fig. 7. Heatmaps of window following the burglary scenario, showing the interior side, in both closed and opened condition, and exterior side. A color gradient shows the proportion of participants who touched each location with darker colors indicating higher proportions and thus higher levels of contact.

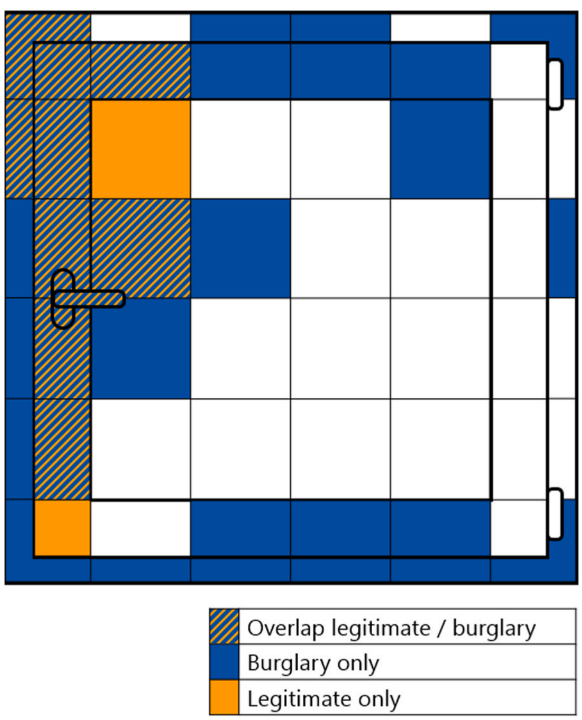

Fig. 8. Overlap between legitimate activity and climbing out.

proportions for both scenarios may still yield relevant traces.

As shown in Fig. 9, most of the locations on the door are more frequently touched in the burglary scenario, as contact proportions were generally higher for the burglary scenario than for the legitimate scenario. With regard to the loiding scenario, only traces found on the mail slot tend to be left more frequently under the legitimate scenario, whereas locations elsewhere may be more frequently touched in the burglary event. With regard to the letterbox burglary, the most apparent finding is that the contact proportions on the mail slot are similarly high in both scenarios (almost all participants touched the mail slot to a certain extent within each scenario), resulting in a difference score close to 0. Yet, if we take the information from the more detailed sublocations of the mail slot into account, we find that the difference scores vary for each of these sublocations. This is due to participants generally touching a higher number of sublocations during the letterbox burglary as opposed to during the legitimate scenario.

Similar to the data obtained on the doors, differences in contact proportions between both scenarios can also be visualized for the windows (Fig. 10). Again, this visualization can only be conducted using the interior side of the window frame, as the inside and exterior side were not recorded for the legitimate scenario. Here, the difference scores indicate that the contact proportions at the different locations do not differ greatly between the two scenarios. The contact proportions for both scenarios are either similar or remarkably low. Only two locations, both on the window frame, show a difference score above 0.1; indicating a higher contact proportion for the burglary scenario.

4. Discussion

By visualizing areas of contact on entry points corresponding to a number of activities, we aimed to determine relevant sampling locations for trace DNA and fingermarks in burglary investigations. The research showed that legitimate activities, such as delivering mail or opening a door and window, resulted in fewer areas of contact and thus an expected low recovery of trace DNA or fingermarks in a real-life scenario. Burglary-related activities on the other hand, resulted in greater distributions of contact, with various contact patterns depending on the activity tested. While testing for two burglary methods produced distinct contact patterns on the doors, no obvious pattern was found on window frames when these were used as part of an entrance or escape route. The heatmap visualizations presented here could inform forensic examiners where to expect trace evidence to be found within forensic practice.

Based on our findings, relevant sampling areas for offender traces on the doors can be found surrounding and upwards from the doorknob when a door is opened through loiding. In the case of a letterbox burglary, the area directly below the mail slot is of main interest. Furthermore, door hardware could serve as another potential source of offender traces, yet may also display high levels of contact from legitimate use in specific sublocations. In situations where the burglary method is unknown or difficult to determine, it would be advisable for the search strategy to include the most relevant sampling areas for both methods. Regarding window frames, no clear answer can be given as to where to specifically find offender traces, as distinct patterns of contact were

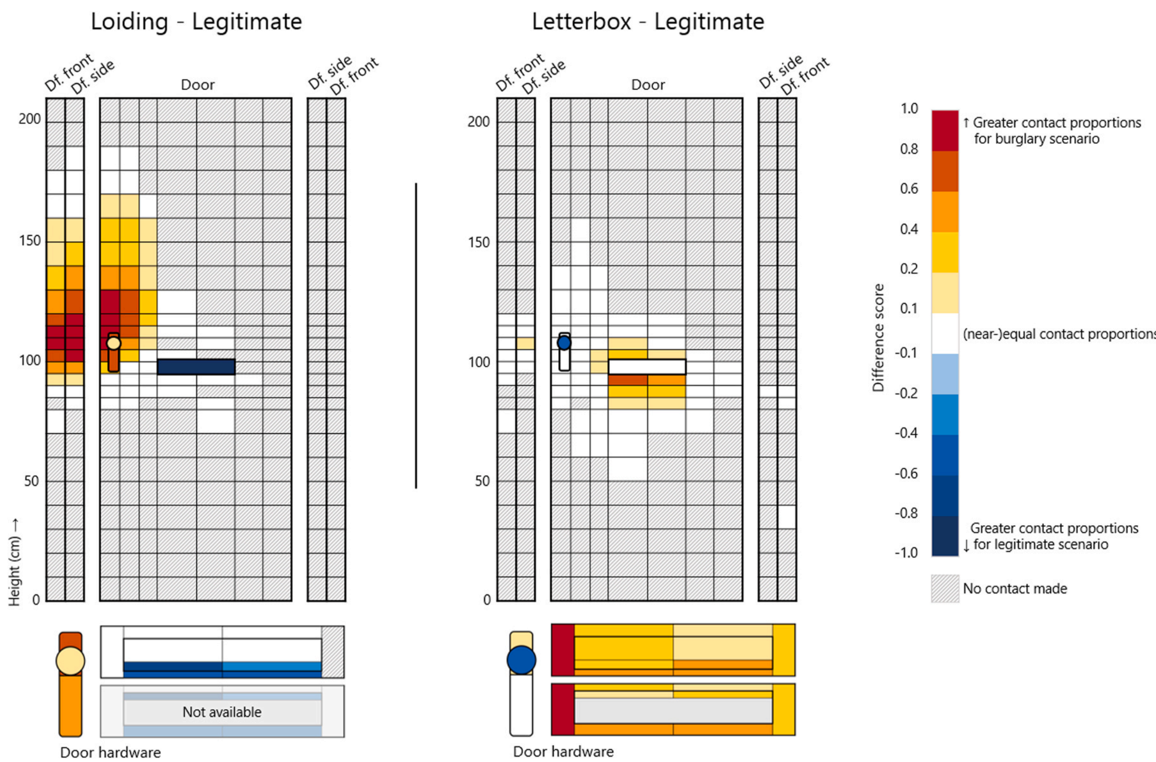

Fig. 9. Overview of difference scores between each burglary scenario and the legitimate scenario. Color gradients indicate whether the contact proportions are higher for the burglary scenario (a positive difference score; red) or for the legitimate scenario (a negative difference score; blue).

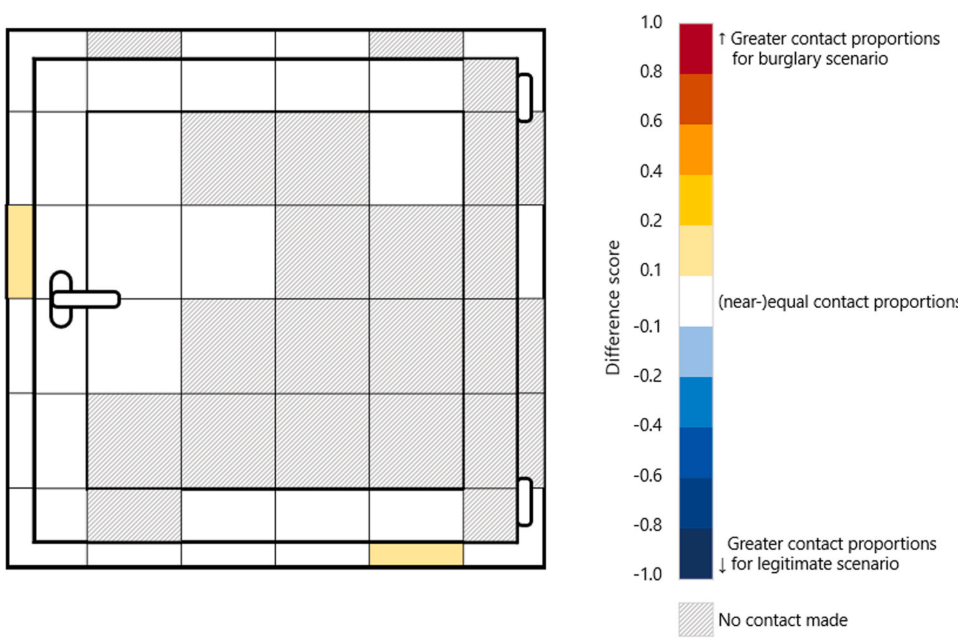

Fig. 10. Overview of difference scores between the burglary scenario and the legitimate scenario. Color gradients indicate whether the contact proportions are higher for the burglary scenario (a positive difference score; red) or for the legitimate scenario (a negative difference score; blue).

absent. If one had to provide advice, both the sides and lower ledge of the window frame may be more favorable. In case of the scenario in which an offender climbed through the window in the other direction (from the outside in), the data obtained from the exterior side of the window may be representative to assess the interior window frame during the examination.

While touch may be a good indicator of where to expect fingermarks and DNA traces to be deposited, it does not necessarily reflect the probability of recovering DNA or fingermarks. Touching a surface does not always lead to a detectable DNA quantity or a fingermark of sufficient quality for comparison, as this is highly dependent on the donor and numerous physical factors [33,34]. Moreover, factors relating to the type of interaction play a significant role in recovering trace material and their influence may differ between DNA and fingermarks. For example, while more friction generally leads to more DNA deposition [33], a similar manner of interaction may be detrimental to fingermark deposition, leaving only smudges as a result. Conversely, trace DNA recovered from a burglary scene does not automatically indicate that a surface has been touched. Mechanisms of DNA transfer other than touch (e.g. breathing or sneezing) may also contribute to the overall trace distribution [35], as well as indirect transfer for example via contact with clothing or gloves [16]. In short, there is no guarantee that the likelihood of trace recovery will equal the likelihood of contact as presented here. Our data nevertheless indicate relevant areas with regard to burglary-related activity and can guide the search strategy.

Given the experimental design, some limitations need to be taken into account when evaluating the use of these findings in forensic casework. Firstly, while conducting the experiment at a music festival had its advantages (e.g. the ability to attract a large number of participants in little time), it could be questioned to what extent these participants were representative of the burglar population. First, alcohol and drug consumption are common occurrences at festival sites, as also indicated by our data. Yet substance abuse appears to be common within the burglar population as well [14,36]. Hence, while the precise effect of intoxication on trace deposition is unknown, we consider this not to be a major influencing factor within the current research design. Second, although some participants claimed to be familiar with the burglary techniques tested, the vast majority had no burglary experience. This is an important aspect to keep in mind, as it appears that experienced burglars differ in their decision-making compared to non-offenders during specific parts of the burglary process [22]. The level of expertise a burglar may possess, however, relies on the length of their criminal career [37]. Part of offenders, and especially young offenders, are therefore likely closer in skill to amateurs. Yet, while we may expect skilled burglars to be more efficient and leave fewer traces behind, it remains likely that they will contact the same areas as inexperienced offenders. This is because the activities tested here require limited skill and are known to also be used by non-offenders when they have been accidently locked out. For this reason we expect that the target areas identified here may be representative for all skill levels. Nevertheless, repetition with known offenders or trained individuals (e.g. police personnel) would be required to establish whether burglary experience actually has an impact on which locations are touched.

Secondly, the possible influence of the paint on participants' behaviour is unknown. By trying to avoid dirtying themselves or simply being distracted by the wet paint, participants may have acted differently than they otherwise would. With the implementation of the time limit as part of the burglary scenario, we have aimed to minimize this potential factor as much as possible. In any case, further research in which DNA swabbing and powder dusting is applied after simulation with bare hands is required to test whether the activities currently investigated indeed lead to contact with the acquired 'hotspots'.

Finally, we recognize that the tested scenarios are a simplified version of the interactions taking place in reality. Especially in the case of the legitimate scenario, it is expected that daily use of the entry points is far more complex than we depicted here, as this likely entails many more activities with many variations, such as leaning on the door or out of a window, window cleaning, holding a door open for another, etcetera. As such, the background level of traces to be found on entry points would originate from an accumulation of multiple activities from various points in time. Here, we only tested three straight-forward activities (delivering mail, using a key and opening/closing), which could explain the reason for the few areas of contact found within this scenario. These findings could also result from low inter-individual variability, indicating that participants approach the activities in a relatively similar manner. If this is the case, it may indicate that legitimate activities lead to a narrow distribution of background traces on these surfaces, which would be in line with the current available research. Aside from handles and windowsills, limited research has highlighted relatively low recovery rates of background DNA from entry points [11,13,20]. If the simulation were to be expanded, a more accurate and representative pattern of contact could potentially be determined. It should be noted though, that to fully understand trace deposition, an endless number of activities could be tested. Experimentally, this is of course not feasible, so simplified scenarios that provide general insights remain preferable.

While the main aim of this study was to generate data that could guide the search strategy at the crime scene, we also believe that the data can be of added value when it comes to interpretation of recovered trace material during both the investigative and evaluative phase. Given the burglary or legitimate scenario, the observation of a trace in a certain location (assuming transfer after touch) may be more or less likely. For example, traces recovered from the left door frame may be more indicative of the loiding scenario, as this scenario resulted in much higher contact proportions in this area compared to the legitimate scenario. However, while the data obtained from the doors appear informative in this regard, the data obtained from the windows showed that the burglary scenario and the legitimate scenario led to near-equal contact proportions, highlighting the similar results found for both scenarios. In the evaluative phase, the contact probabilities presented here may also aid interpretation as part of activity level evaluative reporting. Our findings may be used to feed conditional probability tables (CPTs) on probability of contact within Bayesian networks. To fully benefit from these data, more experimental data need to be collected on the probability of trace transfer, persistence, and recovery (TPR), to a variety of relevant surface materials.

In summary, the current research provides valuable insights into the relationship between activities and the expected locations of traces that could be deposited as a result. By visualization through heatmapping, areas of high and low contact were found that can inform the expected likelihood of trace recovery from certain locations on entry points. This information can be used to interpret trace evidence and provides forensic examiners with data-driven knowledge to support their search strategies in burglary investigations.

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CRediT authorship contribution statement

Yoram R. Goedhart: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Katharina Draxel:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Androniki S.I. Katsikis:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **Christianne J. de Poot:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Ingrid Jullens:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Anouk de Ronde:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Bas Kokshoorn:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

None.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2025.112615.

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