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The persistence of fibres following a choreographed assault: A quantitative assessment of the influence of physical activity

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ABSTRACT

The persistence of textile fibres is influenced by activities undertaken by the wearer; however, few studies have exclusively explored this relationship. This study extends the authors' work described in a previous publication on fibre transfer and aimed to address this gap by investigating the short- to medium-term persistence of textile fibres on a cotton T-shirt and polyester/cotton hoody worn by a 'victim' and 'assailant' transferred following a typical assault scenario. The number, length and spatial distribution of fibres recovered at intervals up to four hours was examined. Furthermore, the influence of performing physical activity of varying intensity on persistence behaviour was investigated.

Results showed that retentive capacity of the recipient textile bears a strong impact on fibre recovery, highlighting two distinct trends. Persistence of cotton and man-made fibres from donor hoodies recovered from T-shirts generally decreased as intensity of activity increased. In contrast, retention of T-shirt cotton on recipient hoodies appeared greatest after high intensity activity (77.5%). The confounding increased recovery in the initial hour (161.8%) indicated the important contribution of fragmentation and attributes of the donor fibre, in addition to physical activity, on persistence. The proportion of shorter fibres generally increased with time and intensity of activity. Crucially, physical activity was more strongly associated with fibre length than quantity of fibres recovered, which has potential implications on evidential value in practice.

The overall project aim was to strengthen the current understanding of fundamental mechanisms implicated in fibre transfer and persistence. This ultimately can be used to inform and support examiners to evaluate fibre findings at the activity level, thereby enhancing the contribution to the judicial system.

1. Introduction

Understanding how traces are generated and 'behave' is at the crux of forensic science and of prime consideration to the forensic scientist [1–5]. In particular, the persistence of traces is a factor of paramount importance throughout all stages of the forensic science process [6]: from setting expectations at pre-assessment, through to interpreting findings within the framework of circumstances at the evaluative stage.

During an incident, including commission of a crime, a person or an object may contact another person, surface or object, thereby transferring textile fibres to these recipients. Previous work has shown extensive deposition and recovery of fibres immediately following transfer can occur [7–9]. However, in practice there is often a variable time delay between the relevant incident (ie. activity causing transfer) and collection of a garment for analysis, during which the garment may have been worn, washed and/or subjected to use. Addressing questions of time plays a significant role transversally in forensic science, yet concurrently remains a fundamental challenge [6,10]. For textile fibres, the likelihood of recovery depends upon their persistence after the transfer event. Consequently, how many have been lost and how many can be anticipated is of interest.

Building on from the seminal works of Pounds and Smalldon [11–13], the persistence of fibres has been demonstrated to be influenced by the interaction of numerous factors, namely the:

- Nature and location of contact (force, pressure) [14,15]
- Characteristics of the recipient textile [16,17]
- Characteristics of the donor fibre [18–20]
- Placement of other clothing in contact with the recipient garment [14]
- Activities of the recipient (wearer) after transfer [8,15,21] and
- Time interval between transfer and recovery [18,22]

Whilst the first four listed also have an impact on the dynamics of transfer, the latter two factors relating to activities of the wearer and time are crucially influential on persistence of these transferred fibres. However, due to the asymmetry of time (one is unable to revisit the past), information about these aspects is often undetermined.

Over the past fifty years, considerable research has examined persistence, yet three key issues remain unaddressed. Firstly, most

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studies have been laboratory-based simulations or small-scale context-specific reconstructions. Whilst these have indeed made significant contributions in advancing our knowledge, it has been disputed they lack realism in modelling real-life situations [23]. Addressing this deficiency would facilitate greater confidence in extrapolating results to contemporary casework scenarios to guide interpretation.

Secondly, much of the literature concerns wool and acrylic fibres [11,12,14,17,24–27]; which were representative of those encountered in practice and relevant to the respective climates at the times of publication. However, the production [28,29], prevalence [30,31] and market demand for cotton and synthetic fibres has since increased [32,33]. The rapid globalisation of the textile industry, advances in textile engineering, rise of fast fashion and increased consumption has largely driven these changes. It is crucial for experts to draw upon a contemporaneous, relevant and representative knowledge base to support robust interpretation. This situation underscores the need for modern data.

And thirdly, despite recognition that activities executed by the wearer of a recipient substrate affect the persistence of transferred fibres, limited research exploring this factor has been undertaken. Salter and Cook [8] demonstrated the dramatic effect of vigorous activity (running) on increasing the loss of fibres from head hair compared to walking. However, running was combined with combing or washing, both of which independently could be considered active removal techniques. Akulova et al. [34] examined fibre persistence in the course of normal daily wear, reporting an increased rate of loss when public transport was used. Palmer & Burch [18] recorded volunteers' activities in their study of fibre persistence on skin but as no target fibres were recovered after 24 hours, were unable to infer any correlation.

This situation emphasises a lack of data supporting our understanding of persistence to appropriately evaluate fibre evidence and address questions of activity, although ENFSI guidelines and a general consensus within the professional community promote addressing propositions at the activity level [35,36]. Despite a growing drive for a more comprehensive understanding of activity level variables [36], much focus remains on concluding at source level [37]. By leaving the onus of interpretation and addressing considerations of activity (including transfer, persistence and recovery) to non-experts [38], the risk of misinterpretation is heightened and the value of fibre and microtrace evidence remains undermined.

Furthermore, the number of studies conducted with ambulatory human subjects that are more representative of real-world outcomes than laboratory-based experiments remain limited. Of these few, none have simulated a common assault until recently [7,9], despite the frequency with which these are reported [39].

The present study extends work described in a previous publication [7] concerning fibre transfer and aims to address this disparity by investigating the persistence of textile fibres on garments worn by a 'victim' and 'assailant' after a typical assault scenario. The number, length and spatial distribution of transferred fibres recovered at intervals up to four hours was examined. Furthermore, the influence of physical activity of the wearer on these parameters was investigated.

2. Materials and Methods

The materials and methodology employed for fibre transfer and laboratory analysis has been previously described [7]. Eight yellow 100% cotton T-shirts (Quoz, Revesby) and eight red cotton/polyester blend hoodies (80% cotton/20% polyester, Sportage Clothing Australia) purchased from a wholesaler were used in the study. The construction and physical properties of their respective textile, yarn and fibres were characterised. Methods specific to the investigation of fibre persistence are detailed below.

2.1. Transfer and persistence scenario

A cohort of 21 volunteers (14 male, 7 female) of intermediate to advanced skill level in jiujitsu (yellow to black belt grade) took part in the study. Each individual was informed of the research objectives and provided written consent to participate. All experiments were approved by the University of Technology Sydney Human Research Ethics Committee (HREC ETH18–3059). Pairs of volunteers performed the choreographed assault transfer simulation, one person assuming the 'assailant' role (red hoody) and the other the 'victim' (yellow T-shirt). As shown in Fig. 1, immediately after the transfer simulation, participants were assigned to maintain a low, moderate, or high intensity of physical activity (refer to **Table S1 in Supplementary Materials**) for a time interval of 10, 30, 60, 120 or 240 min (T10 – T240).

Individuals assigned to the *high intensity* group performed an additional 5 min of aerobic exercises including burpees, push-ups, sprints and star jumps. Upon conclusion they returned training equipment to the storeroom, involving manual lifting, brisk walking and whole-body movements for 5 – 10 min. *Moderate intensity* participants immediately proceeded with equipment pack-up procedures, whilst those in the *low intensity* group refrained from this task. All individual subjects maintained a distance of at least 5 m from the other participant to minimise potential contamination.

When the designated time interval was 10 min, participants remained in the study centre. Garments were removed, repackaged and returned. For all other intervals, participants left the centre and after the designated time, removed and repackaged the garment in the paper evidence bag to submit for analysis. Each combination of physical activity intensity (3) and time interval (5) was replicated four times, resulting in a total of 60 experiments.

2.1.1. Participant questionnaire

Participants wearing garments for longer than or equal to 30 min completed a questionnaire (see Table S5 in **Supplementary Data**) regarding modes of transport, activities they engaged in, nature of interpersonal contacts and surroundings frequented during the time wearing the garment. The survey was delivered in printed hard copy format and online using Google Forms.

Response data was manually collated from printed responses and generated from the online format using inbuilt Google Forms functionalities. Further statistical analysis and visualisation was performed using Microsoft Excel and R [40].

2.2. Laboratory analysis

2.2.1. Fibre recovery

Transferred fibres were recovered from worn garments by zonal tapelifting [41]. Front and back surfaces of T-shirts and hoodies were divided into 16 or 22 zones, respectively. Tapelifts of garment surfaces were acquired to recover fibres, using the "press and rub" method [41,42] with approximately 15 cm lengths of 48 mm wide adhesive tape (Scotch® Tough Grip Moving Tape, 3 M Australia).

Examination procedures and protocols, including passive sampling [43] to monitor pollution from the search room environment, were as previously described [44]. Results of monitoring indicated that on average, fewer than ten fibres were recovered per session when tapelifting hoodies (mean $\bar{x} = 9.1$, median $M = 6$) and T-shirts ($\bar{x} = 6.4$, $M = 5$). These figures were considered acceptable relative to the number of target fibres recovered from the garments.

2.2.2. Fibre analysis

2.2.2.1. Count and identification. Tapelifts were examined by grid searching [41] with the aid of low-powered stereomicroscopy. All fibres including transferred yellow cotton (victim) or red cotton and red man-

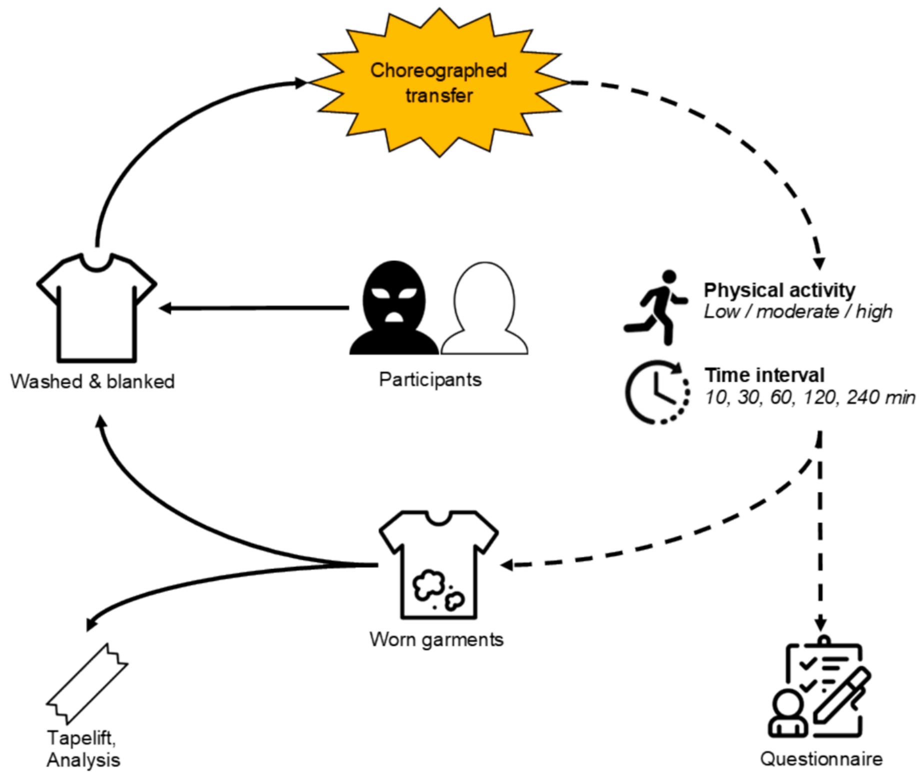

Fig. 1. Schematic representation of persistence studies following simulated transfer.

made (assailant) target fibres were marked, counted and further examined at 50 – 1,000× total magnification for identification and verification (see [7]).

2.2.2.2. Length measurement. A proportional stratified random sampling approach [45–47] was used to create a representative subpopulation of target fibres for length measurement. The whole dataset population was divided into 32 distinct subgroups (strata) based on all combinations of garment type, intensity of physical activity and time (where T = 0 was considered control for activity). The *sample_frac* function [48] from the *dplyr* package [49] in R was used to randomly sample 10% of each stratum, creating a subpopulation of 6,893 datapoints, of which 5,286 were T10 – T240.

The continuous length of each fibre was measured from digital micrographs acquired during grid search examination using Leica Application Suite (LAS) software (v3.8, Leica Microsystems GmbH, Wetzlar) (see [7]). Recorded lengths were categorised into size ranges of ≤ 1.0 mm, 1.0–3.0 mm, 3.0–5.0 mm and ≥ 5.0 mm.

2.3. Statistical analysis

Univariate analysis of variance (ANOVA) was applied to investigate the effects of elapsed time, intensity of activity or fibre size on the number of recovered fibres. Frequency data underwent Box-Cox or $\log_{10}$ transformation to satisfy requirements of normal distribution and homogeneity of variance [50,51]. Tukey's HSD (honestly significant different) test was used for pairwise comparison of means between groups to assess for statistically significant difference, considering a 95% confidence level ($\alpha = 0.05$). Thus, a p-value ≥ 0.05 was considered non-significant; within the range [0.01:0.05] weakly significant; within the range [0.001:0.01] moderately significant; and < 0.001 highly significant.

Pearson's Chi-squared test was employed to test independence between paired combinations of four variables (intensity of physical activity, time interval, target fibre type, fibre size) on the expected number of recovered fibres. Multivariate ANOVA was applied to investigate any interaction effects between independent variables on the persistence of transferred fibres. Balanced two-way factorial ANOVA models were built in which $\log_{10}$ or Box-Cox transformed frequency data was the dependent variable and the independent variables were as previously stated. For models indicating significant main effects and interactions, these impact of the variables were quantified using partial eta-squared (η_p^2) and interpreted as small (0.01), moderate (0.06) or large (0.14) [52,53].

All statistical analysis was performed using R (v.4.2.1) [40]. Packages used for data analysis and visualisation included *MASS*, *lawstat*, *DescTools*, *ggfortify*, *rcompanion*, *lsr* and *AICcmodavg* [54–60].

3. Results and discussion

3.1. Persistence

60 persistence experiments were performed, with the two garment types collected at intervals of 10, 30, 60, 120 and 240 min (T10 – T240). A total of 175,948 fibres were recovered, of which 52,902 (30.1%) were target fibres. Cotton was recovered in greatest numbers, with total count of T-shirt cotton ($n = 23{,}965$) marginally higher than from hoodies ($n = 22{,}437$). Man-made fibres were least abundant ($n = 6{,}500$). Statistical analysis revealed these pairwise differences were significant (Kruskal-Wallis [H(2, n = 175,948) = 82.5, $p < 0.01$]; Dunn's post-hoc $p < 0.05$ all pairs). The relative proportions observed corresponds with results from transfer experiments [6].

As an independent measures study, each timepoint represents an independent experimental replicate. Therefore, the figures presented are not true persistence curves as presented in longitudinal (repeated measures) studies, but nonetheless provide valuable insight to identify overall trends in persistence behaviour of the transferred fibres. Correspondingly, persistence in this context refers to an *estimated persistence*, defined as frequency or frequency decay observed as a function of time from T10.

Results immediately following conclusion of the choreographed transfer simulation (T0) were excluded from the persistence dataset for consistency. Data across both sets were in the same order of magnitude, however absolute numbers varied, and inclusion would likely lead to unreliable interpretation of persistence.

Persistence curves presented in Fig. 2 indicate that on average, considerable numbers of fibres were recovered per garment at each timepoint. After four hours, this ranged from 180 for man-made and 439 to 713 for cotton (from hoody and T-shirt, respectively).

Donor fibres from the hoody showed an overall decreasing trend. The number of cotton and man-made fibres sharply decreased by over 50% in the first 30 min (51.3% and 51.1%, respectively), followed by an approximate exponential reduction. The shape of the curve agrees with the classic two-stage exponential decay model reported in the literature [11,14,18,34]. In contrast, initial reduction in T-shirt cotton was gradual, with a sharp decrease observed between 1 and 2 h.

After 4 h, T-shirt cotton indicated greatest persistence with 44.6% recovery (237 ± 39 [$\bar{x} \pm SD$]). This was followed by hoody man-made (27.9%, 60 ± 24), and hoody cotton with the lowest persistence (18.7%, 146 ± 77). And indeed, Chi-squared test results showed a significant association between donor target fibre type and time on the number of fibres recovered ($\chi^2(8, n = 52{,}902) = 1341.3, p < 0.001$).

It is acknowledged that the persistence of transferred fibres is governed by their mechanical state of binding, namely: ‘weakly bound’, ‘bound’ and ‘strongly bound’ [13,14]. The hoody textile is characterised by a relatively open knit construction with a soft, fuzzy hand feel. The distinctive fuzziness, conferred by the prevalent fibre protrusions on the surface, can be attributed in part to the visibly lesser degree of yarn twist [61,62]. These features combined create a more open three-dimensional network promoting fibre entanglement and retention by mechanical and/or electrostatic forces, thereby facilitating greater persistence (see Fig. 3). In contrast, the T-shirt textile had a smooth texture and tightly knit closed construction, further densified by high-twist yarn. These features in conjunction with the lack of surface fibre protrusions renders it less receptive to binding transferred hoody cotton and man-made fibres.

The findings indicate that characteristics of the recipient textile play a greater role in persistence than those of the donor fibre when considering the number of fibres recovered. Such agrees with a comparable study, however concerning the persistence of acrylic and wool [34].

It is recognised that transferred fibres persist longer on recipient textiles with greater ‘hairiness’ or prevalence of protruding fibres [63], as shown by the fleecy hoody knit [7]. This structural feature is a function of textile construction (eg. shape or form, knit or woven, knit density and yarn construction) and type of fibre in the yarn.

Furthermore, yarn and fibre composition in the textile has a considerable influence on persistence. Previous research showed blended polyester/cotton T-shirt fabric had greater retentive capacity than equivalent garments of pure cotton or polyester [64]. In this present study, the blended composition of the hoody may have contributed to the greater persistence of T-shirt cotton fibres, however as the characteristics and construction of the pure cotton T-shirt textile differed, further investigation with hoodies comprised of 100% cotton and/or 100% polyester would be warranted.

These results present general trends reflecting data combining independently measured variables (ie. physical activity, fibre length), each of which have been established to play a considerable role in persistence, However, the contribution of physical activity on persistence behaviour is explored in section 3.4.

3.2. Location

3.2.1. Front and back surfaces

Overall, more target fibres were recovered from front (58.2%) compared to back surfaces (41.8%) of recipient garments. Considering

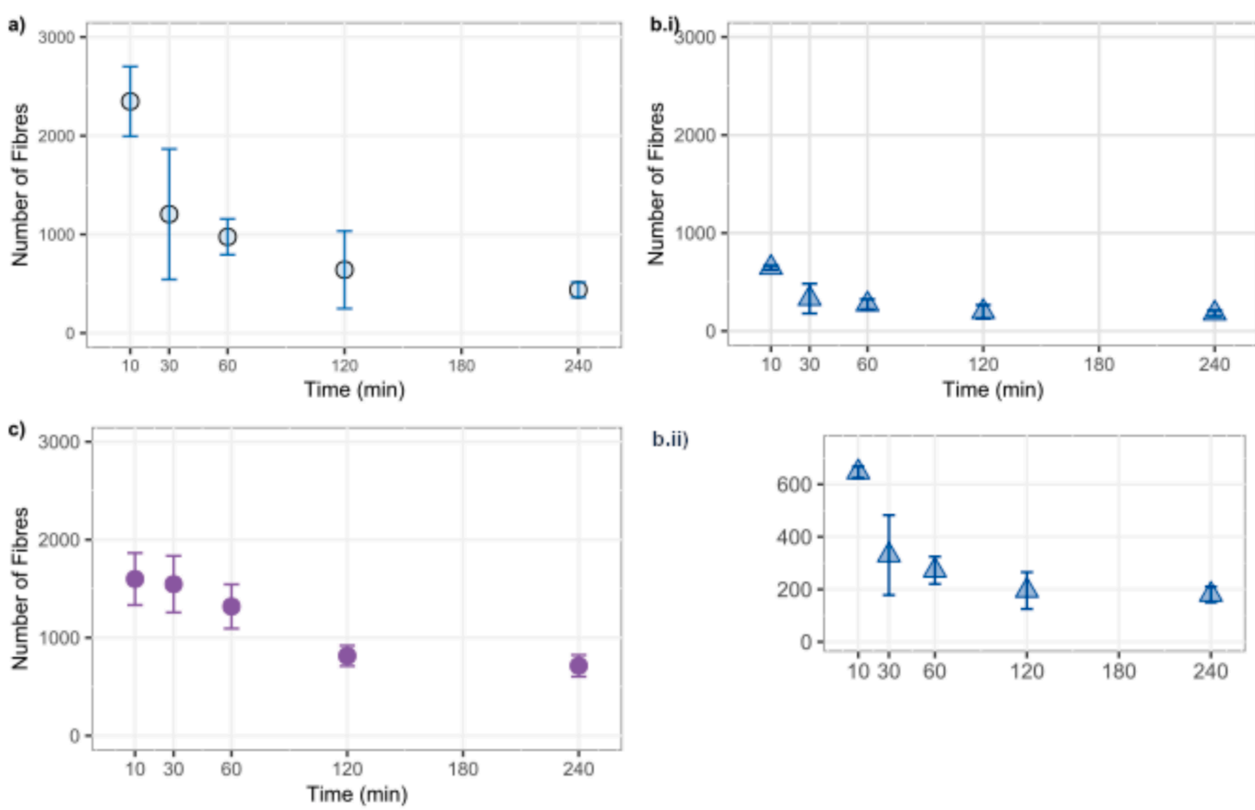

Fig. 2. Mean number of (a) hoody cotton, (b.i) hoody man-made, (b.ii) zoomed-in view of hoody man-made, and (c) T-shirt cotton fibres per garment vs time. Error bars represent 1 SD (standard deviation).

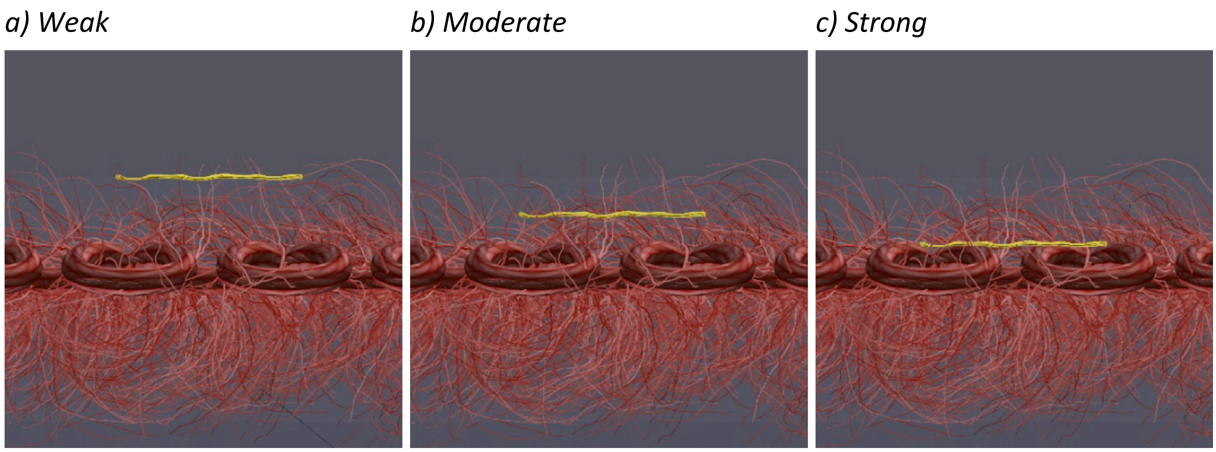

Fig. 3. Graphical representation of a T-shirt cotton fibre in (a) weak, (b) moderately or (c) strongly bound states on the front surface of the recipient hoody textile and relationship with textile construction.

the primarily frontal focus of the choreographed assault, this result is not remarkable. However, as shown in Table 1, the disparity between front and back reduced over time, from a maximum at 30 min for hoody fibres and 10 min for T-shirt cotton, towards a relatively uniform distribution after 240 min. This trend was illustrated by cotton from both hoodies and T-shirts, despite their respective recipient surfaces differing in retentive capacity.

Interestingly, an inverse trend was observed from man-made fibres, whereby a marginally higher proportion was recovered from the front by 240 min (57.1%) compared to 10 min (55.2%). This may be attributable to redistribution and/or relatively greater loss from the back surfaces. However, in this study, man-made fibres from the cotton-polyester blended hoody only transferred to the T-shirt textile as recipient. Further experimentation with a wider range of recipient textiles would be warranted to investigate if this observation is a general pattern or specific to the context of the experimental conditions.

Fibre loss can be due to gravity (falling following dislodgement and transferring to the environment) and contact with another garment, item or surface (secondary transfer). Participants were instructed to not wear an overgarment after the simulation, as this promotes loss [14]. However, as experiments were conducted at the end of a workday, participants were often observed to carry a shoulder bag or backpack. Secondary transfer to personal articles as these may account for loss from the back surface. These details were not recorded but is a worthwhile consideration for future work.

The practical significance of these results is that it is indeed advisable to examine both front and back surfaces of garments, even in situations where a front-dominant contact or transfer event is hypothesised. Limiting recovery exclusively from the front presents a risk of disregarding potentially valuable traces that may contribute to a more comprehensive interpretation of the findings in reconstruction of the activities that may have occurred. Furthermore, recovery and analysis of personal effects to explore the potential of secondary transfer is also due consideration, as guided by case circumstances.

Table 1
Proportion of target fibres recovered from the front surface of garments at T10 – T240 (n = 52,902).

Target Fibre on Front	Time (mins)				
	10	30	60	120	240
Hoody cotton	60.6%	65.3%	61.6%	61.9%	57.7%
Hoody man-made	55.1%	64.2%	57.1%	58.1%	57.1%
T-shirt cotton	59.2%	54.4%	51.7%	54.8%	53.7%

3.2.2. Zonal distribution

Of the 30,804 target fibres recovered from the front surfaces of recipient garments, their distribution according to tapelifting zones as a function of time was investigated. For the purposes of this paper, a *section* comprises multiple *zones*, the latter which correspond to those outlined in 2.2.1.

Fig. 4 shows that man-made fibres from hoodies were predominantly recovered from the upper right zone and right sleeve 10 min following transfer. However, after 30 min there was no clearly discernible trend in zonal distribution.

In contrast, hoody cotton was largely recovered from both sleeves (25.8% [T240] – 32.8% [T120]) and upper sections (28.0% [T240] – 33.1% [T120]) of recipient T-shirts. Despite considerable variation amongst the eight zones at each time point, a relatively uniform distribution across all zones (11.0% [lower left] – 15.4% [upper left]) was observed by 240 min.

Recovery of T-shirt cotton was likewise greatest from sleeves (14.9% [right, T30] – 20.3% [left, T60]), followed by the middle body section (19.4% [T10] – 20.8% [T240]) of recipient hoodies. However, in contrast to hoody cotton, zonal distribution over time showed little variation (upper and lower zones of sleeves combined). Additionally, the proportion of fibres on sleeves was consistently higher on the left than the right side at all time points.

The sustained unilateral predominance ("sidedness") of T-shirt cotton on the recipient textile reflects the pattern of zonal distribution immediately following transfer. Such an observation in practice is valuable for event reconstruction and interpretation given questions of activity. However, it is to be remarked that the magnitude of the difference (1.2% [T120] – 4.7% [T240]) may not necessarily be considered significant. Consequently, further investigation into the effect of handedness of the wearer and individual variations in execution of the choreographed sequence are required, possibly aided by video recording of the transfer event. Additionally, considerations of redistribution in packaging following collection, redistribution and secondary transfer during wear, nature and types of activities performed during the time interval and further replicates warrant further experimentation to establish the recurrent nature of this observation or if such are specific to the current context.

Findings concerning fibre location, both empirically and in practice, require caution in interpretation [27]. The greater the timeframe between transfer and recovery requires consideration of the effect of specific movements of actions performed, locations frequented and contact with items presents indeterminable opportunities for redistribution, secondary and multiple transfers, many of which may not be known or determinable.

Overall, results demonstrate that the time elapsed between transfer

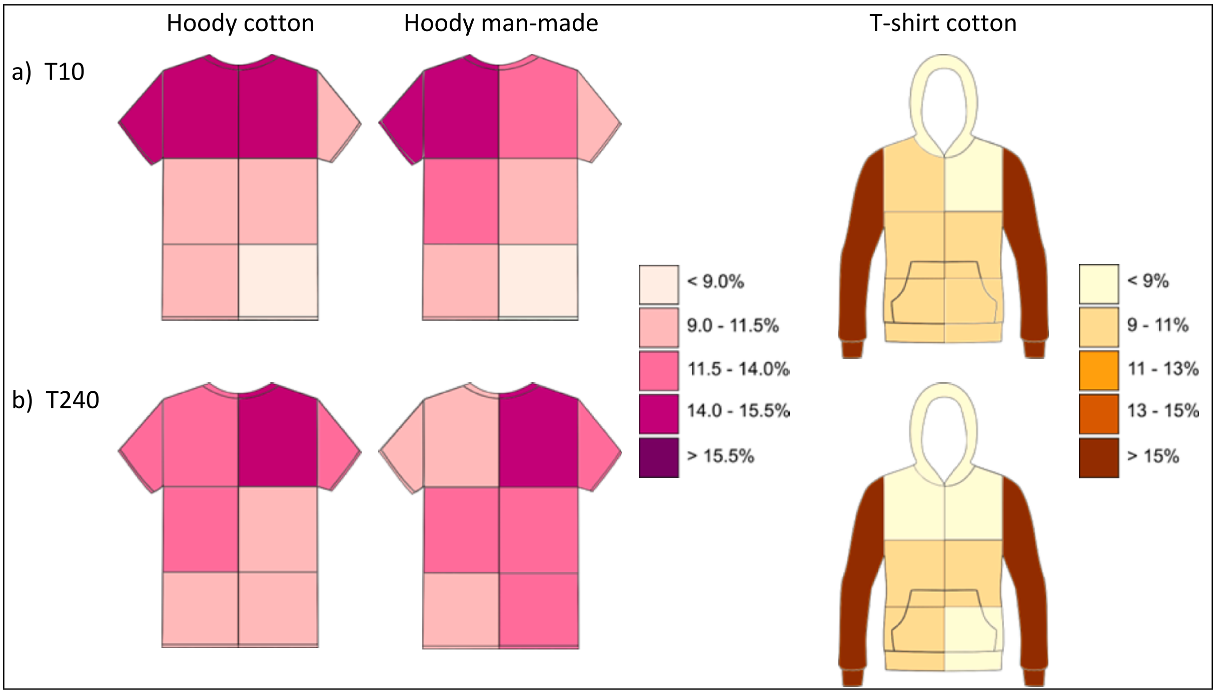

Fig. 4. Zonal distribution of target fibres on the front surface of recipient garments at T10 (a) and T240 (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

and recovery affect the location of fibres. For donor fibres on a less retentive recipient textile, the fibre distribution became more uniform over time. The unknown activities of wearer are also of important consideration, and further examined in section 3.4.

3.3. Length

From the subpopulation of 5,286 target fibres, their length distribution as a proportion by target fibre is shown in Fig. 5. In general, the proportion decreased as fibre length increased. Shortest fibres (< 1.0 mm) were most prevalent, followed by those 1.0–3.0 mm. It was relatively uncommon to recover fibres > 3.0 mm.

The dominance of shortest fibres (< 1.0 mm) in hoody cotton (61.9% compared to ~ 40% for man-made and T-shirt cotton) clearly depicted this trend, with their proportion 2.5 times greater than those 1.0–3.0 mm (24.5%). This difference in magnitude between the first two size groups was shown to be statistically significant (Tukey's HSD: $p < 0.001$) but was not the case for the other target fibres. However, two notable deviations to this trend were evident. Firstly, 1.0–3.0 mm T-shirt cotton fibres were marginally more prevalent (44.9%) than those < 1.0 mm (41.3%). Secondly, the proportion of man-made fibres > 5.0 mm was greater (13.9%) than those 3.0–5.0 mm (11.3%). However, statistical analysis indicated both differences were not significant (Tukey's HSD, $p > 0.05$).

Long fibres (> 3.0 mm) were represented at the greatest proportion by man-made fibres from hoodies, of which approximately a quarter were longer than 3.0 mm (25.3%).

Collectively, over 85% of cotton fibres (hoody and T-shirt) were < 3.0 mm. Despite commonality of fibre type, their respective donor and recipient textiles had differing sheddability and retentive capacities. This suggests that the intrinsic characteristics of the donor fibre are stronger determinants of fibre length distribution than recipient textile characteristics.

Examination of length distribution over time revealed that whilst proportions of the longer fibre groups (3.0–5.0 mm and > 5.0 mm) of hoody cotton remained relatively unchanged, the magnitude of difference between the two shorter groups became smaller. As shown in Fig. 6, a steady increase in the proportion of short fibres (1.0–3.0 mm) was accompanied by a decrease in the shortest fibres (< 1.0 mm). In contrast, T-shirt cotton exhibited a relatively uniform pattern (order and magnitude). There was a gradual shift towards 1.0–3.0 mm lengths by 4 h.

The distribution pattern of man-made fibres was more complex. There was an initial marked predominance of shortest fibres (< 1.0 mm), but from 30 to 120 min, distribution of all size ranges remained relatively unchanged. Of particular note is the apparent shift towards longer fibres after 4 h.

From these observations, it appears an interplay between characteristics of the recipient textile in combination with characteristics of the donor fibre affect the pattern of length distribution over time. This can be understood to occur from two concurrent mechanisms:

1. preferential loss of certain sized fibres due to mechanical forces; and
2. breakage of existing fibres, thereby increasing the quantity present.

Firstly, the construction of the hoody textile facilitated stronger binding and greater persistence of T-shirt cotton (see 3.1). This can partly account for the relatively consistent length distribution observed over time, particularly evident for longer fibres which may be tightly bound within the lofty three-dimensional mesh network of the textile (Fig. 3**c**). The variation shown by the shorter fibres suggests existence in all three states of binding: located amongst the protrusions above the textile surface (Fig. 3**a**); in the subsurface (Fig. 3**b**); and deeply buried in the network. Conversely, the smoother and lower retentiveness of T-shirt textile may account for the greater variability seen for hoody cotton. The initial loss of man-made fibres < 1.0 mm indicates those weakly bound or on the surface fibre protrusions.

Secondly, breakage or fragmentation is a function of the fibres' physical properties. Recovery of longer man-made fibres may be anticipated to be low, as longer fibres are generally lost more readily than shorter ones. However, this loss is countered by the greater robustness and breakage resistance of man-made fibres that minimises a predominance of shorter fibres.

However, the distribution pattern of hoody cotton requires consideration of more complex mechanisms and their interactions. An

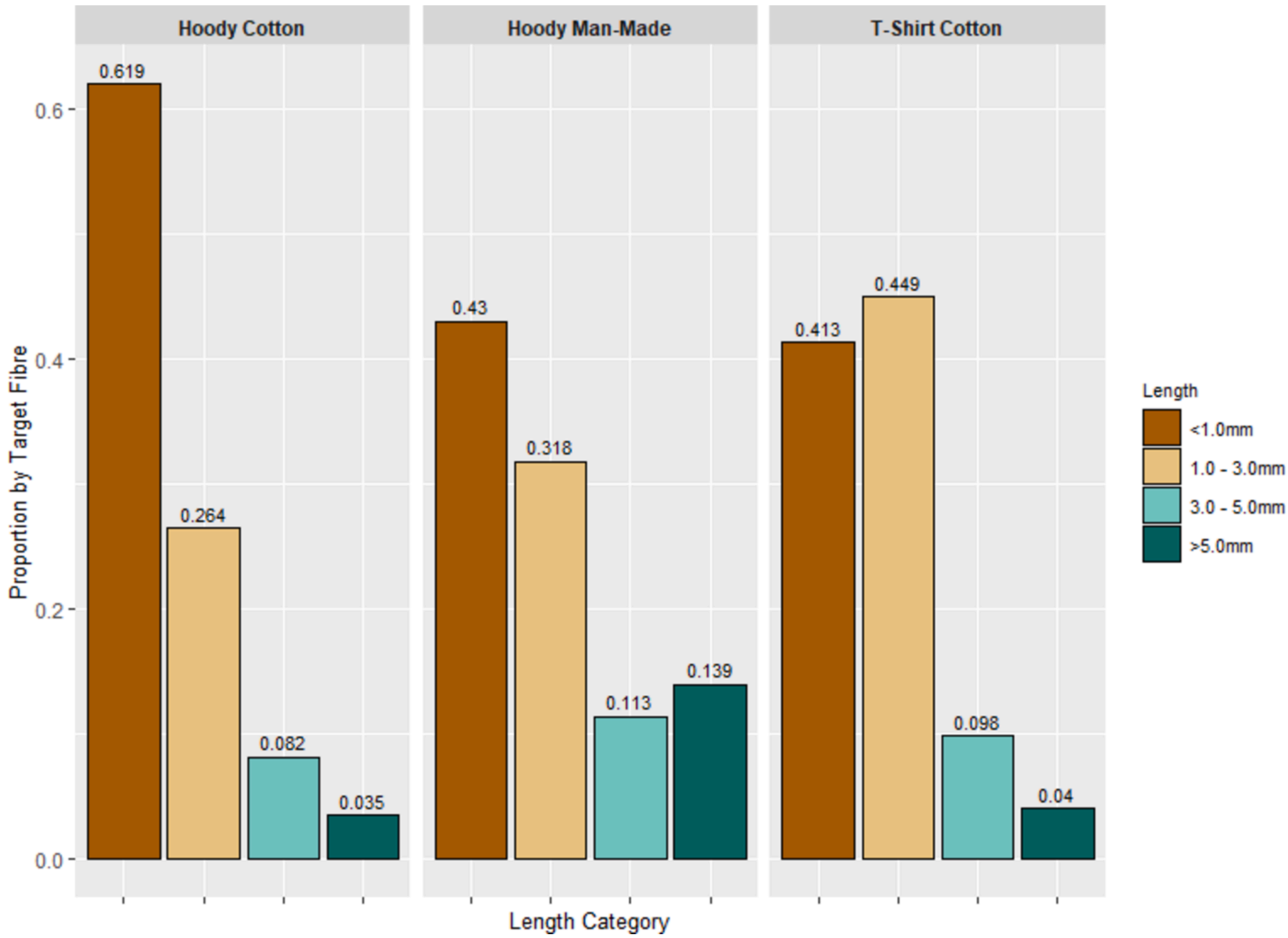

Fig. 5. Fibre length distribution of data subset T10 – T240 presented as a proportion by target fibre (*n* [hoody cotton] = 2,246, *n* [man-made] = 582, *n* [T-shirt cotton] = 2,458). (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

expected initial reduction in the proportion of shortest fibres (as seen for man-made) was not observed. Cotton, as a natural fibre, is more brittle and breaks more readily than man-made fibres. Loosely bound fibres at the surface, sub-surface and atop the fibre protrusions are susceptible to loss in addition to fragmentation from friction during wear. Therefore, other external variables, including the activities of wearer (section 3.4), warrant consideration alongside textile and fibre characteristics.

Contrary to expectations and previous findings, these results suggest greater loss (lower persistence) of shortest fibres. However, the literature presents conflicting reports that shorter lengths persist more than longer ones [14,22]; remain constant [11]; or that there is no clear trend [8]. This discrepancy can in part be due to variations in fibre types, recipient surfaces and experimental conditions employed in each study. Consequently, this situation underscores the importance of contextual information being made available and taken into careful consideration when interpreting results of fibre analyses.

3.4. Physical activity

3.4.1. Frequency

The number of fibres recovered per garment as a function of intensity of physical activity is shown in Fig. 7. Greatest numbers were observed after moderate activity: with hoody cotton being most prevalent ($\bar{x}$ = 578 ± 452); closely followed by T-shirt cotton ($\bar{x}$ = 495 ± 256) and man-made ($\bar{x}$ = 175 ± 132) fibres.

There were no distinct differences amongst target fibres between low and high intensity levels in terms of magnitude and order of distribution. Results of post-hoc pairwise analysis supported these observations, showing no statistically significant differences for all three target fibres (Tukey's HSD $p > 0.05$). However, T-shirt cotton returned the greatest numbers after low ($\bar{x}$ = 360 ± 137) and high intensity activity ($\bar{x}$ = 342 ± 132). Furthermore, an inverse relationship was shown by target fibres from the hoody, with fewest recovered after low ($\bar{x}$ [hoody cotton] = 253 ± 173, $\bar{x}$ [man-made] = 72 ± 31), and high activity ($\bar{x}$ [hoody cotton] = 289 ± 291, $\bar{x}$ [man-made] = 77 ± 50).

Physical activity appeared to have little effect on the variation in the mean number of T-shirt cotton fibres recovered. In comparison, hoody cotton exhibited a more than two-fold variation in mean as a function of physical activity (253 [low], 578 [mod]). These observations were corroborated by results of one-way ANOVA, which indicated the mean number of hoody cotton and man-made fibres showed statistically significant variation across the three intensity levels of activity ($p < 0.001$), but this was not the case for T-shirt cotton ($p > 0.05$). The number of recovered fibres thus depends more so on the characteristics of the recipient textile than the wearer's intensity of physical activity.

Fibre loss can be considered to occur due to a combination of three mechanisms, with which physical activity of the wearer overlaps. These are, namely:

1. Contact with recipient garment itself,
2. Contact with other surfaces,
3. Gravitational loss and/or interaction with the air

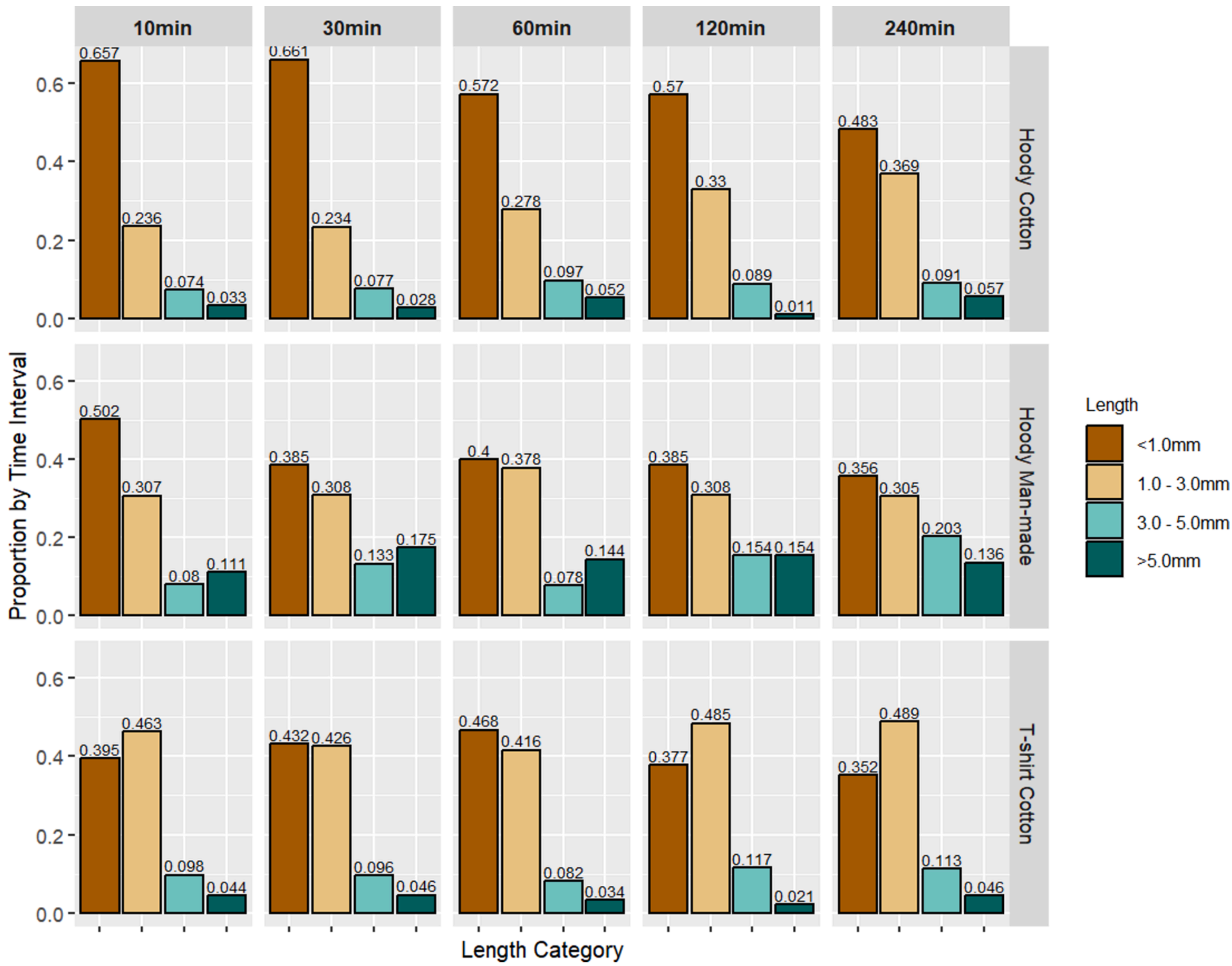

Fig. 6. Length distribution of target fibres as a proportion by time interval 10 – 240 min. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

Firstly, garments may exhibit self-contact and transfer from friction, resulting in redistribution and loss to the environment (falling). The inward-facing regions of arms brushing against the side or front of the body have previously demonstrated greater loss than less disturbed areas [14]. Similarly, the shape and fitment of the garment to the wearer can be anticipated to affect the likelihood of such occurring. For example, an oversized or 'baggy' article is likely to have greater surface area of free fabric able to contact with itself than a form-fitted garment. The construction and dynamics of the garment also affect the degree of movement and contact with itself, for example if the textile is stretchy or rigid. In this study, T-shirts were generally worn as a regular or 'comfortable' fit, whereas a higher proportion of hoodies were worn relatively looser. These variables combined with the mechanics of physical activity may have contributed to the variability observed in hoody fibres.

Secondly, direct contact with external surfaces results in transfer to the environment. This may be other items, or garments (worn by people). In this study, overgarments were not to be worn by participants. However, this is not to exclude transfer by interpersonal contact, brushing past another individual in a crowd (eg. public transport) to more extensive contact in an embrace or the wearing or carrying of backpacks and bags (see 3.2.1).

And thirdly, fibre loss can occur in the absence of contact. The movement of air and associated mechanisms (creating currents, external forces in three dimensions that can initiate dislodgement) in addition to gravitational loss does not necessitate direct contact. Contactless transfer by airborne fibres [65] has been empirically shown to occur, but is unlikely a major contributing factor in this context.

This is contrary to expectations of greater persistence from a more sedentary subject (ie. performing a low level of activity) than a more active subject. This is as increased motion and frequency of frictional forces would be anticipated to accelerate loss. It is apparent that intensity of physical activity is not necessarily proportional to the extent of loss; and additional factors are implicated in affecting the number of fibres recovered following activity.

3.4.2. *Persistence*

The effect of physical activity on the persistence of transferred fibres is shown in Fig. 8. Initial loss was clearly greatest in hoody cotton after high intensity activity, marked by a 63.8% decrease in mean numbers recovered per garment after the first 30 min (697 ± 425 [T10], 252 ± 72 [T30]). Conversely, moderate activity indicated greatest persistence, reflected by a relatively modest 35.2% decrease in the same time interval (1,144 ± 193 [T10], 741 ± 565 [T30]). Man-made fibres showed an opposite trend, with moderate activity indicating greatest initial loss. Furthermore, there was no distinct variation amongst the three

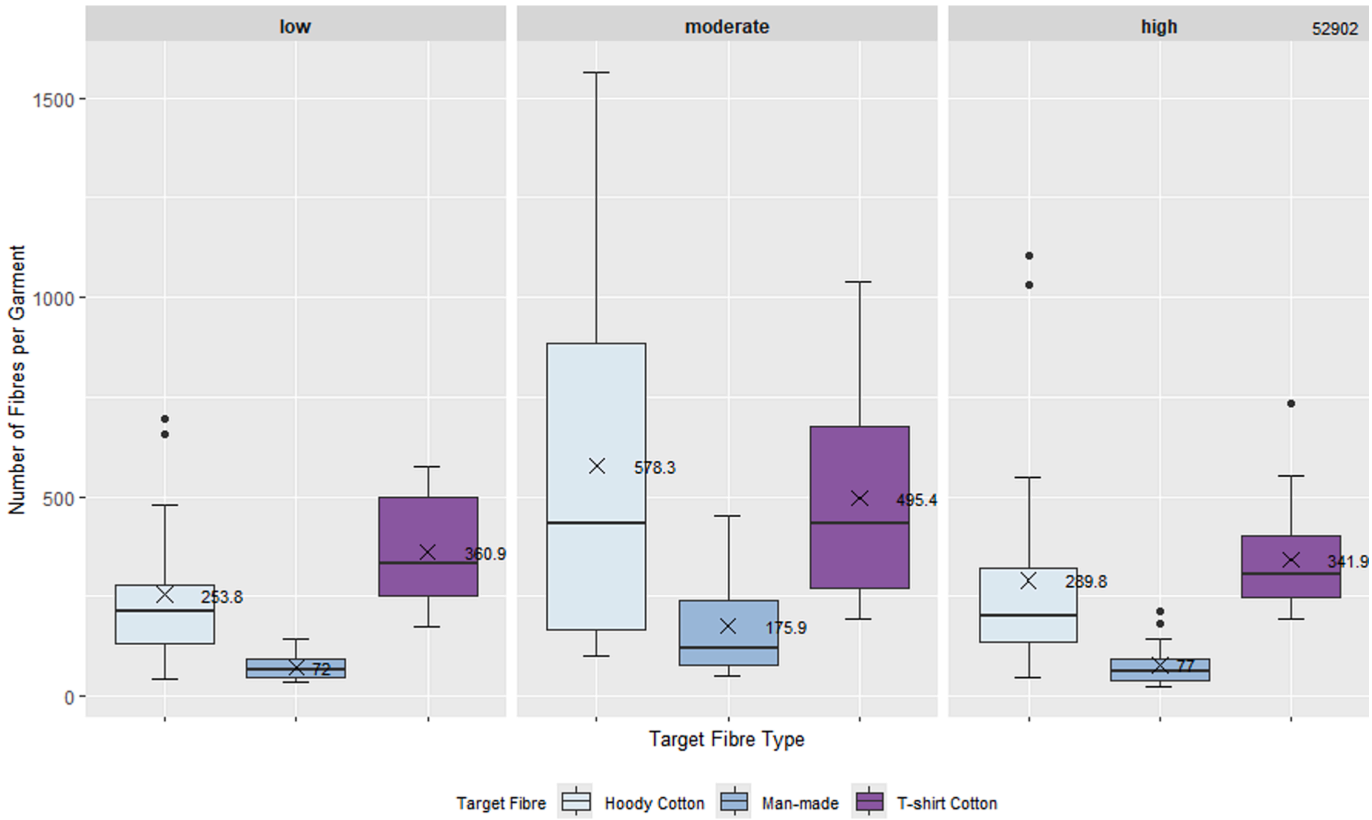

Fig. 7. Boxplot distribution of the number of fibres per garment as a function of intensity of physical activity following transfer. Mean values have been annotated. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

intensities of activity after the first 30 min (42.5% [low] – 52.9% [moderate]).

After four hours, retention of hoody cotton was greatest after low activity (41.5%), whilst moderate and high intensity activity returned approximately 12%.

Persistence of hoody man-made fibres appeared to decrease as intensity of activity increased. After 2 h, the highest proportion was recovered after low (43.3%), followed by moderate activity (28.2%). High activity resulted in extensive loss such that a stable threshold (25.5%) was reached by two hours. Interestingly, loss continued beyond this threshold after moderate activity, with 17.6% recovered after four hours. These distinctions indicate that persistence is not predominantly dependent on characteristics of the recipient substrate. Such corresponds with previous findings which suggest inherent characteristics of the donor fibre have a greater role in the first few hours [34].

Persistence curves for T-shirt cotton fibres were characterised by unique features, but varied with intensity of activity. Retention was greatest after low (42.7%) activity after 4 h, also shown by both hoody fibre types. Interestingly, a similar number of fibres were recovered after low (235 ± 50) and high (240 ± 24) activity. Despite commonality of generic fibre type, these figures are approximately three times greater than observed for hoody cotton (75 ± 26 [low]; 37 ± 7 [high]), indicating that the differing characteristics of the recipient textile are a predominant influence on the higher persistence of cotton from T-shirts.

High intensity activity resulted in an unexpected increase within the first hour. This phenomenon depicts underlying fragmentation mechanisms progressing at a faster rate than fibre loss. The external torsional and multidimensional contact forces associated with intense activity facilitate accelerated fragmentation of T-shirt cotton fibres loosely or moderately bound at the textile surface. Resultant smaller fragments are more likely to remain on the fuzzier hoody textile (increasing fibre count) and undergo further fragmentation. The inflection point of the curve after an hour (T60 – T120) indicates an equilibrium between the concurrent processes of fragmentation and loss, beyond which the rate of loss supersedes fragmentation. After low activity, it can be understood that fragmentation and loss initially proceed at similar rates. After 30 min, fibre loss predominates, as reflected by the steady decrease. In contrast, more loss occurs compared to fragmentation following moderate activity. Fig. 9 provides a visual summary of these observations.

It is widely acknowledged that contact and frictional forces are important factors in the initial transfer of fibres [12,13]. Fibres transferred with higher pressures are lost more slowly [14], which has been attributed to mechanical interactions between the recipient fabric and transferred fibres. Consequently, it can be inferred that greater contact pressures implicated in the assault scenario would encourage deeper entanglement of transferred T-shirt cotton fibres into the network of surface fibre protrusions and internal mesh construction of the hoody knit, constituting a more strongly bound state. Applied force was not a measured nor controlled variable in the current study, however future work employing wearable pressure sensors [66] could facilitate further investigation.

For quantitative assessment of the contribution of the variables physical activity and elapsed time on the number of fibres recovered, data were subjected to statistical analysis. Results of Chi-square tests of independence indicated significant relationships between intensity of physical activity and persistence for each target fibre type ($p < 0.001$). As illustrated in Table 2, subsequent analysis with two-way ANOVA showed both main effects of physical activity and time explain a significant amount of variation in the number of hoody cotton fibres recovered. However, the interaction between these factors was not shown to be statistically significant. In contrast, interactions between physical activity and time had significantly large effects on the persistence of hoody man-made and T-shirt cotton fibres.

Measurement of effect size (η_p^2) [67,68] revealed that time alone had

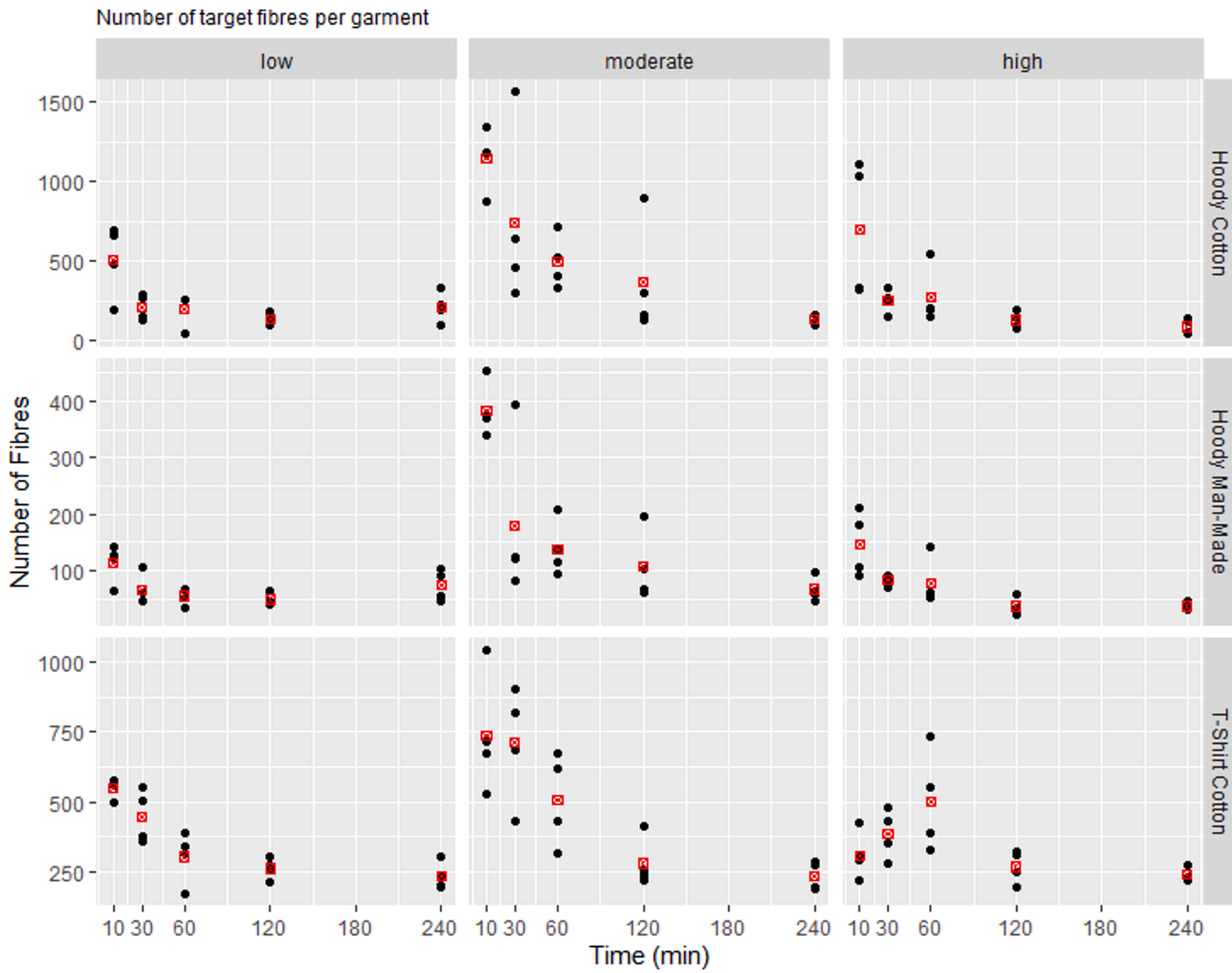

Fig. 8. The total number of recovered hoody cotton, hoody man-made and T-shirt cotton fibres recovered per garment as a function of time (min) and intensity of physical activity. Mean values are indicated in red. (For interpretation of the reference to colour in this figure caption, the reader is referred to the online version of this paper.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

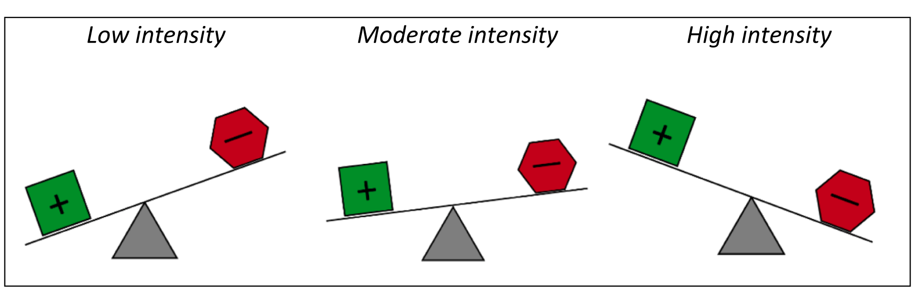

Fig. 9. Predominance of fragmentation (+) and loss (–) in the initial 30 min during different intensities of physical activity on the persistence of T-shirt cotton fibres.

a greater effect than intensity of activity for all target fibres. The interaction effects between activity and time ($\eta_p^2 = 0.398$) were greater than activity alone ($\eta_p^2 = 0.256$) for T-shirt cotton, but smaller for man-made hoody fibres ($\eta^2_{p\,activity:time} = 0.295$; $\eta^2_{p\,activity} = 0.542$).

Despite categorisation of physical activity into three levels of intensity, the qualitative nature of this variable is a potentially confounding factor that likely resulted in intersubject variation for a given stratum of physical activity. Regardless, this study is arguably one of the first in forensic science to compare categorisation of degree of general physical activity (aside from eg. running vs walking) despite it being a qualitative measure often applied in other disciplines.

3.4.3. Length

A general shift to a greater proportion of shorter fibres as intensity of physical activity increased was observed. However, closer examination revealed variations according to donor fibre type.

Hoody cotton consistently displayed a sequential descending order of size distribution. Additionally, the proportion of shortest fibres (<1.0

Table 2
Summary table of two-way ANOVA results considering factors of time and physical activity.

Effects	Hoody cotton Significance[a] (p-value)	Effect size[b] (η_p^2)	Hoody man-made Significance (p-value)	Effect size (η_p^2)	T-shirt cotton Significance (p-value)	Effect size (η_p^2)
time	high < 0.001	large 0.541	moderate < 0.01	large 0.644	high < 0.001	large 0.658
activity	high < 0.001	medium 0.282	moderate < 0.01	large 0.542	moderate < 0.01	large 0.256
activity*time	non-significant >0.05	–	moderate < 0.01	large 0.295	moderate < 0.01	large 0.398

[a] *non-significant where p-value ≥ 0.05; weak [0.01:0.05]; moderate [0.001:0.01]; and high < 0.001.*
[b] *η_p^2: large > 0.14, medium 0.06, small 0.01.*

mm) increased with activity from low (50.4%) to high (68.9%) intensity, as depicted in Fig. 10. This was accompanied by a reduction in shorter lengths (1.0–3.0 mm). T-shirt cotton presented contrasting results, with shorter fibres almost twice as prevalent (52.4 ± 5.2%) than the shortest (28.8%) after low activity. The proportion of these two categories remained similar after moderate and high activity (range: 39.7%, 48.9%).

The distribution of man-made fibre sizes displayed marked uniformity following low activity. As intensity of activity increased, a shift towards adopting the stepwise descending sequence was observed, suggesting an inverse relationship between length and frequency. Whilst short fibres (<1.0 and 1.0–3.0 mm combined) were consistently most prevalent, it is to be highlighted that longer fibres (3.0–5.0 and > 5.0 mm combined) accounted for almost 30% after high activity, a figure

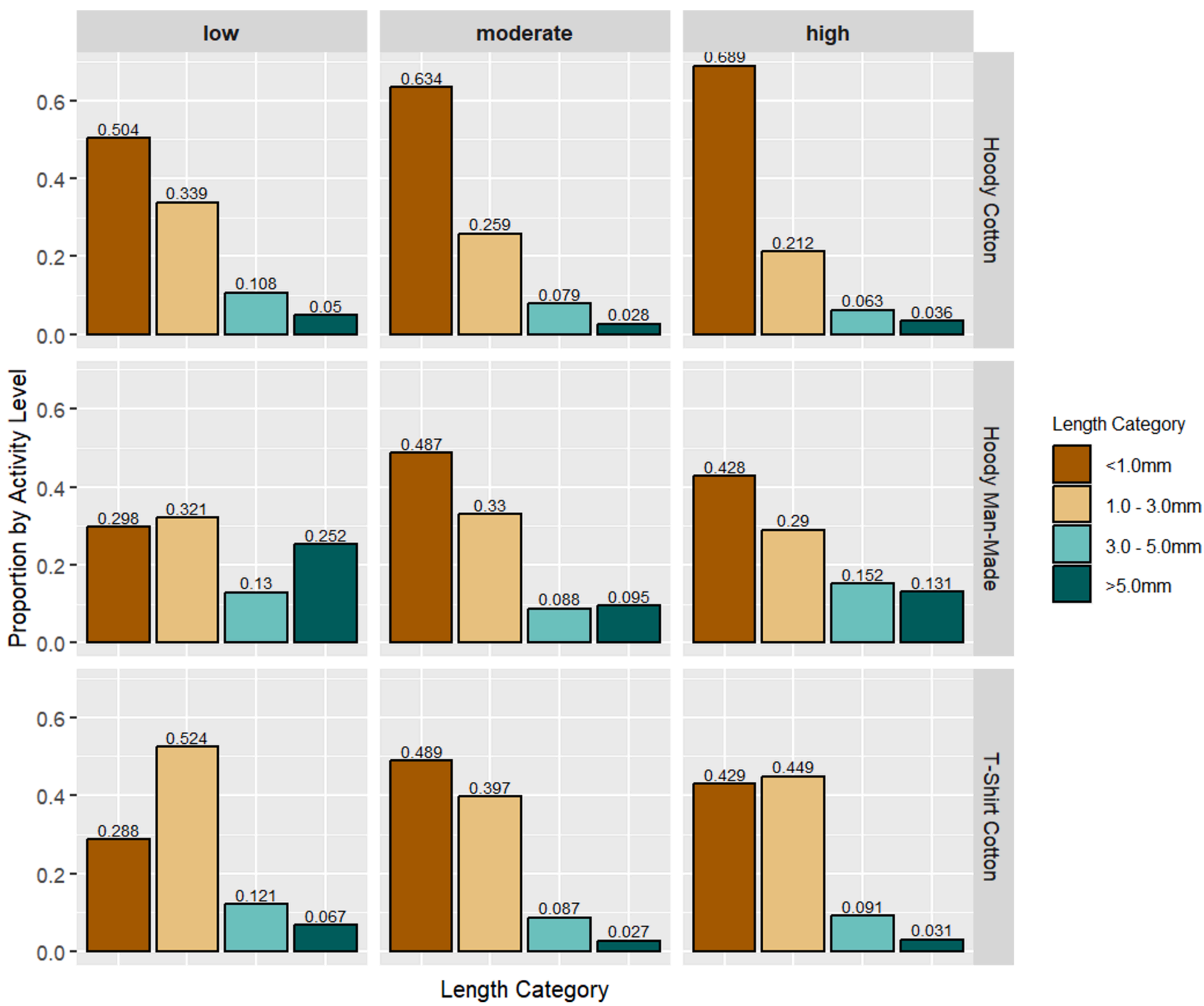

Fig. 10. Length distribution of target fibres as a proportion by intensity of physical activity. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

three-fold greater than observed for cotton from hoodies (9.9%) and T-shirts (12.1%).

An association between intensity of physical activity and length was indeed shown to be statistically significant for each target fibre ($p < 0.001$). However, the dominant contributing factors appear to be a function of characteristics of both the donor fibre and recipient textile, as supported by ANOVA results shown in Table 3. Length was found to have a main effect of high statistical significance ($p < 0.001$) on the number recovered for each of the target fibres, as did physical activity for hoody cotton ($p < 0.001$) and man-made ($p < 0.05$) fibres. Interestingly, whilst the main effect of activity was not significant for T-shirt cotton, a two-way interaction effect between intensity of physical activity and length was shown to be significant for T-shirt cotton and hoody man-made fibres ($p < 0.01$). No statistically significant interaction effect was observed for hoody cotton. The main effect of length was the most important factor for all three target fibres, followed by the interaction effect for hoody man-made and T-shirt cotton fibres, and the main effect of physical activity for hoody target fibres.

The apparent inverse correlation between these two factors shown by cotton can be attributed to the physical properties of natural fibres. Their characteristic brittle nature combined with increasing frictional forces and repeated contact instances from physical activity facilitate accelerated fragmentation. Consequently, features of the recipient textile indirectly govern the number and size of transferred fragmented fibres depending on their state of binding.

It is evident the complex interplay of many variables, including the mechanics of movement and various torsional forces, influence fibre breakage, transfer and loss. Although beyond the scope of this study, further consideration of these concepts, and the behaviour in other natural fibres and textile constructs is warranted to gain insight into the fundamental mechanisms underlying transfer and persistence.

Overall, there is a clearer association between intensity of physical activity and fibre size than solely the number of fibres recovered. Depending on case circumstances, closer examination of length distribution may enhance the evidential value of fibre findings. Additionally, the importance of taking into consideration the recipient textile properties when interpreting length profiles of recovered fibres is also not to be underestimated.

3.4.4. Location

Target fibres from hoodies showed greater preferential zonal distribution than cotton from T-shirts. This disparity was marked after moderate activity, with most recovered from upper zones and sleeves, as shown in Fig. 11. In contrast, low activity saw a relatively uniform distribution across all zones.

The distribution of T-shirt cotton was relatively consistent as intensity of activity varied. Fibres were predominantly localised to the sleeves of hoodies, with a slight majority (up to 3 – 4% difference) on the lower half towards the wrist. The body section remained considerably uniform, with the middle zones most populated (10 – 12.5%).

3.4.5. Participant survey responses

Overall, the 84.4% (81/96) survey response rate was evenly distributed between garment types, and thus results are considered representative of the sample population modelling the variables tested [69]. However, it is to be noted that 50% (18/36) of responses from participants performing moderate activity were returned and may not be a robust representation of that subgroup. The data nonetheless provides valuable insight, warranting its inclusion.

Public transport (train and/or bus) was used by most respondents (92.6%), which has been shown to lead to greater initial loss, likely from incidental contact with various surfaces [34]. Thus, greater persistence could be anticipated from subjects who did not take public transport. Across the 6 subjects who exclusively used private transport, the number of recovered target fibres was generally in the upper quartile of the data range for the same time and activity level of public transport users. However, the small sample size and influence of multiple other factors limits extrapolation of an overall trend.

A wide range of indoor, outdoor, private and public spaces were frequented by all participants. The majority of respondents spent time outdoors (75%) and/or in public settings (63%). Over 60% spent time in a private home environment (50/81), of which most were in the low activity subgroup (29/50, 58%). These results illustrate that during wear, transfer of target fibres and background pollution to and from these environments is to be considered when interpreting the recovered fibre profile.

Discrepancies between participants' self-reported duration of wear and their allocated time interval were observed, with six garments worn for longer than assigned. Two were from the same experimental pair following moderate activity (T-shirt and hoody worn for 120 min instead of 60 min) which following correction had minimal effect on persistence results.

However, three hoodies from the high intensity activity subgroup were worn for 120 min instead of 60 min. Correction for this deviation addresses the anomalous trend observed from T-shirt cotton results. As shown in Fig. 12, the mean per garment at 60 min decreased and correspondingly increased at 120 min. Consequently, an apparent plateau in fibre recovery between 30 and 120 min indicates greater contribution of fibre loss over concurrent fragmentation mechanisms in the first two hours.

The novel employment of a structured survey facilitated rigorous examination of the contribution of environmental and physical activity variables on the persistence of transferred fibres in a real-world context. Such contrasts with previous studies involving human participants, in which it is not reported how information regarding their activities were recorded [8,18,34]. Outcomes also highlight that caution is to be taken in the design, execution, and interpretation of unsupervised persistence studies in which participants' self-reported responses are unable to be objectively verified.

Future work could necessitate participants returning to the study centre to remove the garment; however, this introduces a limitation to the environments to which they are exposed. For example, public transport and home would less likely be frequented by those attending

Table 3
Summary table of two-way ANOVA results considering factors of intensity of physical activity and fibre length on the number of recovered target fibres.

Effects	Hoody cotton *Significance[a] (p-value)*	*Effect size[b] (η_p^2)*	Hoody man-made *Significance (p-value)*	*Effect size (η_p^2)*	T-shirt cotton *Significance (p-value)*	*Effect size (η_p^2)*
activity	high < 0.001	mod-large 0.101	weak < 0.05	moderate 0.044	non-significant > 0.05	–
length	high < 0.001	large 0.517	high < 0.001	large 0.146	high < 0.001	large 0.681
activity*length	non-significant > 0.05	–	moderate < 0.01	mod-large 0.119	high < 0.001	mod-large 0.082

[a] *non-significant where p-value $\geq$ 0.05; weak [0.01:0.05]; moderate [0.001:0.01]; and high $<$ 0.001.*
[b] *η_p^2: large $>$ 0.14, medium 0.06, small 0.01.*

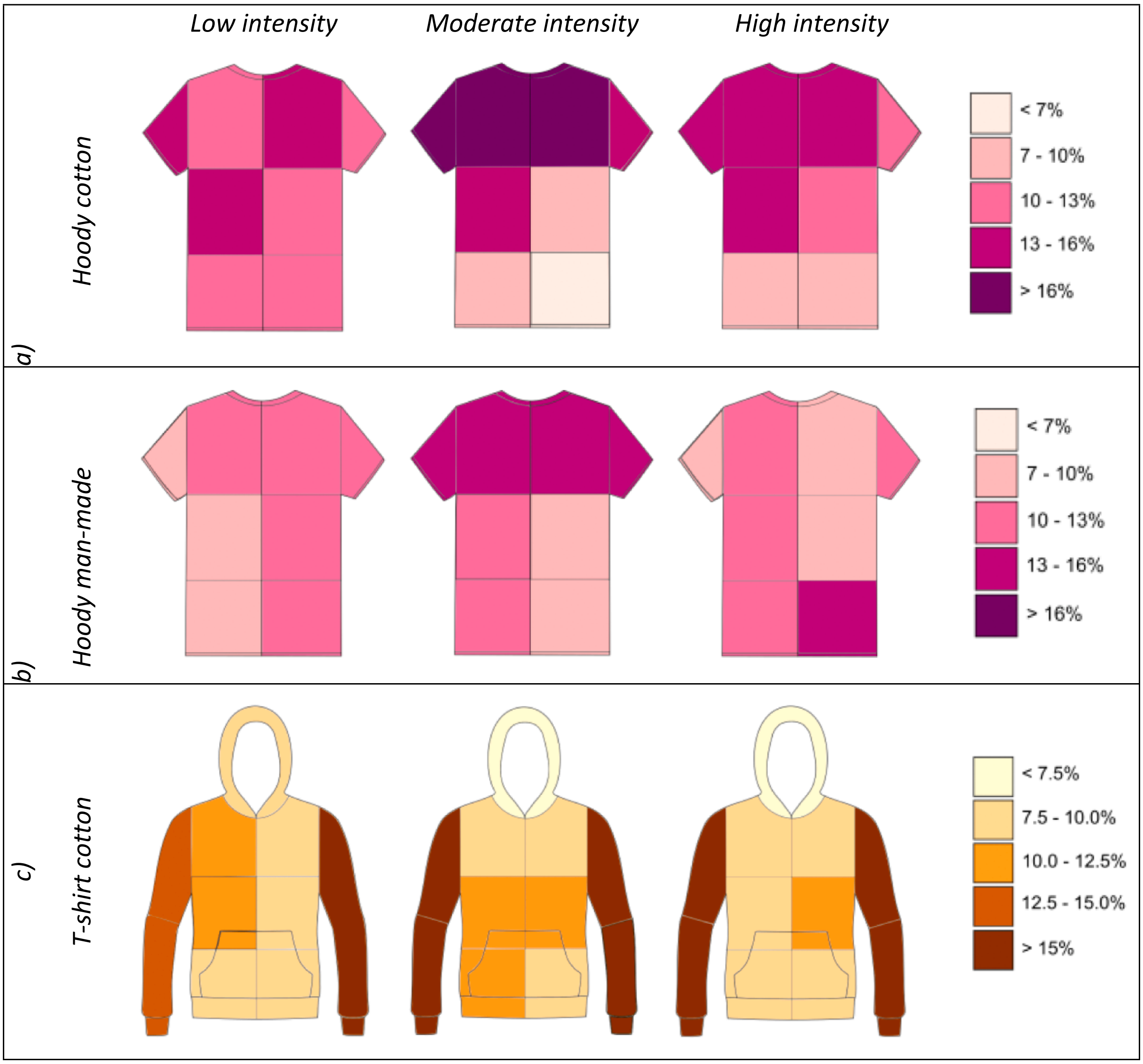

Fig. 11. Proportional zonal distribution of a) hoody cotton (n = 13,839), b) man-made (n = 3,763) and T-shirt cotton (n = 13,202) fibres on the front surface of recipient garments following (L to R) low, moderate, and high intensity physical activity. Upper and lower zones of sleeves have been combined. (For interpretation of the references to colour in this figure legend, the reader is referred to the online version of this paper.).

work and/or school during the day. Nonetheless, combining findings from such an approach with those from the current study conducted in the evenings, may provide for a more global and representative profile.

4. General summary and conclusion

The persistence of fibres has long been recognised to be affected by the activities of the wearer. Greater knowledge about this factor could significantly enhance the evidential value of fibre traces, however research in this area is limited.

This study addresses these gaps in knowledge by investigating the behaviour and persistence of fibres transferred in a simulated assault scenario. Furthermore, it presents targeted empirical support for the contribution of the wearer's activities on persistence. 60 experiments were carried out with participants undertaking physical activity of a low, moderate or high intensity for intervals up to 4 h. The number, length and spatial distribution of fibres recovered was examined.

Characteristics of the recipient textile were shown to be a stronger determinant in overall persistence than those of the donor fibre. After 4 h, cotton from T-shirts had greater estimated persistence than cotton and man-made fibres from hoodies, owing to the greater retentiveness conferred by the surface hairiness and construction of the recipient textile.

Fibre recovery was marginally greater from front than back surfaces of garments. However, the magnitude of the disparity decreased over time towards a more even distribution. In practice, an imbalanced distribution reflective of the transfer activity may be observed within the first 30 min, but the effects of potential redistribution and secondary transfer necessitates caution to be exercised when interpreting locations in a recovered fibre profile.

Physical activity demonstrated significant effects on the persistence of all target fibres. Generally, greater retention was observed after low intensity activity, however, there was no consistent trend across each target fibre type. This was supported by results of two-way ANOVA revealing an interaction effect between physical activity and time had a large influence for hoody man-made and T-shirt cotton fibres, but not hoody cotton. This may be explained by consideration of characteristics of the fibre types and textiles implicated.

Variations in fibre length distribution profiles were shown to be influenced by a dynamic interplay between both donor fibre and

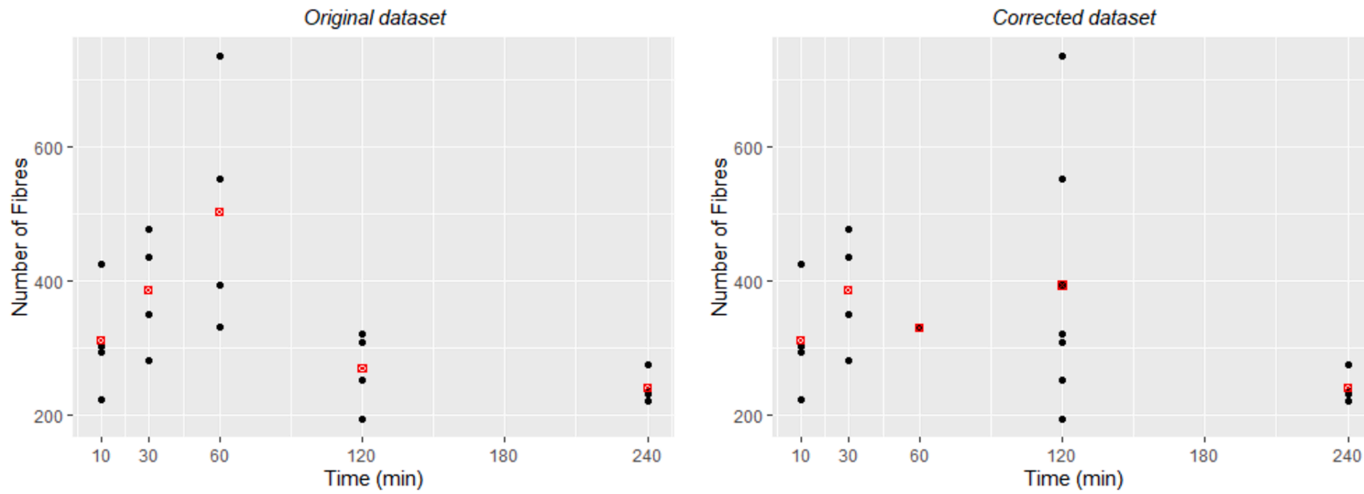

Fig. 12. Number of T-shirt cotton fibres following high intensity activity from original (left) and survey-corrected (right) data. Mean number of fibres per garment is shown in red. (For interpretation of the reference to colour in this figure caption, the reader is referred to the online version of this paper.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recipient textile characteristics, in addition to the balance between concurrent mechanisms of loss and fragmentation (of natural fibres including cotton). Fibres < 1.0 mm in length were more readily lost than short fibres (1.0 – 3.0 mm), contrary to previous research.

The findings suggest a clearer association between physical activity and length, rather than quantity, of recovered fibres. In practice, the evidential value of such findings may be underestimated in certain circumstances if higher length thresholds are used to guide examination.

Overall, the persistence of fibres is a complex and dynamic multifactorial phenomenon. Persistence in initial stages appear governed by characteristics of the donor fibre, with fragmentation of hoody and T-shirt cotton being a major contributor. This was markedly illustrated by increased recovery of T-shirt cotton after high intensity activity. At later timepoints, persistence is largely determined by attributes of the recipient textile. Further work extending the range of recipient textiles with differing construction and composition to investigate the nature of the physical interactions should be undertaken.

In the empirical context of this study, the recovery of fibres within two hours of transfer may prove greater evidential value in informing about the nature of the transfer activity and subsequent actions of the wearer. Additionally in practice, examination of fibre length may prove more informative than numbers of fibres alone regarding activities of the wearer. This is particularly pertinent where cotton (and other natural fibres) and highly retentive recipient substrates are implicated.

This study provides valuable insight into the short- to moderate-term persistence behaviour of textile fibres transferred between garments in a typical assault and the influence of the wearer's activity, that has broad real-world applicability. A greater understanding of the fundamental mechanisms in persistence has also been developed, that can be used to guide case expectations, assessment and assist examiners in the evaluation of textile fibre findings addressing questions of activity. This will ultimately enhance the value of fibre evidence to the judicial system.

5. Ethics Statement

All experiments were approved by the University of Technology Sydney Human Research Ethics Committee (HREC ETH18–3059) and conducted in accordance with the principles embodied in the Declaration of Helsinki. Each individual participant was informed of the research objectives and provided written consent to participate.

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CRediT authorship contribution statement

Victoria Lau: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Claude Roux:** Conceptualization, Supervision, Writing – review & editing, Project administration. **Xanthe Spindler:** Conceptualization, Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scijus.2025.01.004.

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