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The effect of tape type, taping method and tape storage temperature on the retrieval rate of fibres from various surfaces: An example of data generation and analysis to facilitate trace evidence recovery validation and optimisation

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ABSTRACT

This paper aspires to assist those tasked with data generation and analysis for the purpose of the validation and/or optimisation of trace evidence recovery. It does so via a detailed report of the authors' approach to this problem in the context of target fibre retrieval using self-adhesive tapes.

Textile fibres can provide valuable evidence at both source and activity levels. This ability stems from their near ubiquity in the man-made environment, their potential for high levels of discrimination (especially when found in combination) and their reproducible transfer and persistence behaviours. To realise this value for the criminal justice system, it is vital that police forces and forensic providers are collectively able to search for, recover and analyse fibres found at crime scenes and correctly evaluate their evidential value.

ISO accreditation provides quality assurance for such activities. The work reported in this paper was part of a study to validate crime scene fibre retrieval processes for the purposes of ISO17020 accreditation. However, it is hoped that it will be of assistance to those wishing to validate and/or optimise forensic fibre recovery whether at the crime scene or in the laboratory. Further, the methods described may be of value to those who need to validate and/or optimise the recovery of other types of trace evidence.

This paper outlines a series of experiments that investigated the effect of four factors on the rate at which target fibres could be recovered from surfaces by tape lifting. The factors were tape type (with two levels, namely: J-LAR and Crystal Tabs), tape storage temperature (three levels: −5 °C, room temperature [19 ± 1 °C] and 35 °C), taping method (two levels: zonal and one-to-one) and surface (12 levels: each being a surface type commonly encountered at crime scenes). This resulted in 144 unique experimental conditions. For each of these, five repeat fibre recovery rate determinations were carried out, generating 720 data points. All surfaces were clean and dry prior to target fibres being transferred and recovered. In all cases, the tapes were applied to the surfaces at 19 ± 1 °C.

These experiments showed that the surfaces can be divided into three stable clusters based on the median and interquartile range of the fibre retrieval rate achieved from each of them. Also, they showed that, in terms of the proportion of the target fibres retrieved, *typically* and setting aside interaction effects:

- Crystal Tabs outperformed J-LAR;
- rolls of tape stored at −5 °C and 35 °C outperformed those stored at room temperature;
- one-to-one taping outperformed zonal taping.

However, notably, a good degree of between-condition overlap was also apparent in the data. To understand this, a four-way factorial ANOVA model was built which revealed significant and substantive effects for all four main effects and for 10 of the 11 interactions. Importantly, the four-way interaction term was amongst those found to be significant. The interplay between the effects of the four factors was analysed by means of simple effects tests and pairwise contrasts. Tables and interactive parallel coordinate plots have been created. Using

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these it can easily be seen which of any given pair of levels of each of the four factors resulted in the higher fibre retrieval rate under any one of the unique conditions of the study, and the effect size and statistical significance of this observation.

Qualitative evaluations of the effect of tape storage temperatures on tape pliability and its propensity to tear in use were also made.

1. Introduction

This paper is intended to show an example of how data may be gathered and analysed to facilitate the validation and optimisation of trace evidence recovery by forensic practitioners.

Fibres are readily transferred and are slow to degrade in the vast majority of crime scene environments. Furthermore, whilst common as a class, individual fibre types can be rare in their own right or when found in combination. As with other forms of particulate evidence, and in keeping with Locard's principle of exchange [1], they can be evaluated at both source and activity levels. For these reasons, they are of significant forensic value, especially in cases involving violent contact [2].

Keutenius et al. [3] list six attributes that an ideal method of fibre recovery would possess, namely the ability to "*recover all types of fibres from all types of substrates, selectively collect recently transferred fibres; be cost effective; be portable; be simple and quick to perform; minimise contamination potential*". Several methods are available for the retrieval of fibres evidence from surfaces found at crime scenes. These techniques include the removal of such evidence with self-adhesive tape (i.e. tape lifting), vacuuming, scraping and combing [4]. Of these, tape lifting is the most common. The preference for this is often due to its ease of use, its ability to systematically process a specific area, and, in any one instance, its ability to reduce contamination and allow the search for target fibres through the containment of the lifted material between the tape and an acetate sheet [5]. Although the collection of fibres with tapes is relatively easy, the subsequent search for target fibres can be difficult if a thick layer of background fibres and/or other debris is also retrieved. On objects that prove problematic to tape lift, due to shape or fragility, the use of a statically charged wand has proved to be an effective alternative [3].

When using tape to retrieve fibres, there are two main methods that can be applied: zonal and one-to-one (or 1:1) taping [6]. The former involves using a single piece of tape multiple times to cover an identified area. In contrast, one-to-one taping involves covering the area to be processed in individual pieces of abutting or slightly overlapping tape. This method, in which each piece of tape is applied to the surface once only, is usually the one applied to bodies, but may also be applied to other objects [7]. The main perceived benefit of one-to-one taping over zonal taping is its ability to identify the exact location where a specific fibre was retrieved from, further aiding the reconstruction of events. This is called fibre mapping, where a distribution map of fibres is created. This is not solely possible with the one-to-one taping method; zonal taping has also been advocated for the creation of distribution maps [7]. The main drawback of one-to-one taping is that the analysis process can be highly time-consuming and logistically difficult due to the large number of tapes produced [6,8]. Compared with zonal taping, it is also slower to apply during fibre recovery.

A range of tape types is available for retrieving fibres from crime scenes, examples of which are shown in Table 1. Such types vary in size, adhesiveness and the presence or absence of backing. An investigator's choice of tape type might be influenced by tape availability and/or cost, the type of surface from which the fibres are to be retrieved, and personal preference.

The most common surfaces subjected to fibre retrieval are textiles, such as items of clothing from suspects and victims. Research has been carried out on garment surfaces, including that by Schotman & van der Weerd [9] and Wael, Gason & Baes [5]. Schotman & van der Weerd investigated the recovery of fibres from various garments using a variety of different tapes and found that there was very little variability in the efficiency[1] of the tapes, all producing high retrieval rates (85.8%–97.5%) [9]. Wael, Gason & Baes seeded fibres into fabric chairs to investigate the retrieval rates using five different tapes and found that much lower and a larger range of retrieval rates were seen (23.5%–61.0%) [5] compared to the Schotman & van der Weerd study [9].

The tape types under study here are J-LAR and Crystal Tabs, both of which are available to UK police forces for use at crime scenes [10]. As a requirement of ISO accreditation, it is important to investigate the efficiency of these tapes and to understand their limitations, especially when being used in the varied environments of crime scenes [11]. It is also important to identify the efficiency of these tapes on surface types other than garments as these are not the sole surface type from which fibres evidence is retrieved.

There is only one study reported in which the fibre retrieval properties of J-LAR were investigated [9]. This concerned its use with garments, not other surface types. Furthermore, there are no reports of research into the fibre retrieval effectiveness of Crystal Tabs. In addition to this, the method in which the tape was used: either zonal or one-to-one taping, is very rarely identified in the relevant literature.

The introduction of the use of ISO 17020 accreditation for crime scene work provides the need to validate and verify all processes used at crime scenes; ensuring the most effective methods are used. Ideally, validation studies should utilise simulated casework materials in their design to mimic real-life scenarios and ultimately provide recommendations and caveats of use that are fit-for-purpose for crime scene work [11]. In order to provide caveats for the use of lifting tape and to develop robust Standard Operating Procedures (SOPs), variables beyond those already published in the literature needed to be tested. Such tests would help inform practitioners about the optimum storage of tapes and most effective tape lifting method.

The research reported here was conducted as part of a validation project for Warwickshire & West Mercia Police Forces for ISO 17020 accreditation. Its principal aim was to quantitatively assess the rate of fibre recovery of J-LAR and Crystal Tabs tape whilst exploring key variables that may impact on this parameter. These variables were surface type, method of taping (zonal or one-to-one) and tape storage temperature. The last being included because tapes stored in crime scene examiners' vehicles are exposed to various ambient temperatures. A subsidiary aim of this work is to facilitate recommendations for tape lifting that take into account other practicalities that are important when processing crime scenes, such as tape pliability and whether the tapes tear when used. By these means, this study will help inform the most effective choice of tape and taping method when retrieving fibres from crime scenes.

One of the aspirations of the authors is to provide an in-depth analysis of the data obtained in the study reported here. The goal is to give clear indications of the value of the data in making validation and/or optimisation decisions concerning the rate of fibre retrieval using self-adhesive tape for those forensic practitioners tasked with making such decisions. In particular, the authors have striven to evaluate the statistical significance and the effect size of each of the comparisons

[1] Note that in this paper, the terms efficiency and retrieval rate are used interchangeably.

Table 1
Fifteen types of lifting tape available at the time of writing (May 2017).

Tape	Uses	Manufacturer
ISA Lifting Tape	Lifting fingerprints and fibres	WA Products
J-LAR Tape	Lifting fingerprints and fibres	WA Products
1:1 Tape	Lifting fibres using the 1:1 method	WA Products
Crystal Tabs Tape	Lifting fingerprints and fibres	WA Products
Warrender Tape	Lifting fingerprints and fibres	WA Products
Poly-Tape	Collecting fibres on curved surfaces	Polizei
Lifting Tape Polizei crystal clear	Gathering fibres and microtraces	Polizei
Filmolux S23	Gathering fibres and gunshot residue	Neschen
Filmolux S50	Gathering fibres and gunshot residue	Neschen
Filmolux 609	Gathering fibres and gunshot residue	Neschen
Lifting tape 609 with pull tab	Collecting fibres and gunshot residue	Neschen
Hawe 9000	Collecting fibres	Hawe Hugentobler
Low Tack	Collecting fibres	Etilux
High Tack	Collecting fibres	Etilux
Scotchmark Tape	Collecting fibres	3M

made between the pairs of fibre retrieval rates that are given in this paper. The authors also hope that their approach to experimental design and data analysis will be of value to those who may wish to adapt it to inform the optimisation and/or validation of other trace evidence retrieval practices. Details of the data analyses carried out are given in Section 2.3 of this paper and reference is made there to where all of the raw data and the computer code used to analyse it can be found. Also provided in that section are indications of further reading which may be of assistance to those unfamiliar with the statistical methods used.

The police forces involved in the work reported here had a strong influence over the experimental design, and the choice of the tape types used was theirs. Readers interested in comparing the performance of a wider range of tape types are referred to the work of Schotman & van der Weerd [9], and Wael, Gason & Baes [5].

The motivation for this study is grounded in the need for the validation of fibre recovery with self-adhesive tape as carried out by police forces. It might be expected, therefore, that the surfaces included would be limited to examples of those that would normally be processed at the crime scene (such as glossed MDF). However, this is not the case as it also includes surfaces, such as garments, that would commonly be processed in a laboratory setting. The reason for the inclusion of this latter class of surface is that there are circumstances when these are processed within police forces. For example, fibres may be recovered from garments during the *in situ* taping of a dead body [12, Chapter 10] and there are police forces which have in-house laboratory facilities for evidence recovery [for example, see 13]. Also, in an attempt to maximise the utility of the study, the authors opted to choose surfaces with a wide range of surface roughness.

The authors hope that the inclusion of a wide range of surfaces will mean that the findings of this study are of use to both those who work in crime scene processing and those who do so within a laboratory setting. However, it is not the intention of this work to make recommendations concerning which tape type, tape storage temperature and taping method should be used to retrieve target fibres from any given surface. Instead, it is written to empower those charged with making such choices with data to allow them to make better informed decisions. Based on the findings presented in this paper, the authors have created and are now refining two interactive web applications (web apps), one for SOP developers and the other for SOP users [14]. The SOP developer web app allows both the acceptance (i.e. validation) and recommendation (i.e. optimisation) criteria to be set for incorporation into the SOP user web app. The setting of the acceptance criteria is beyond the scope of this paper save to say that, in order to comply with the stipulations of the UK's Forensic Science Regulator, this will have to be done based on an assessment of the end-user requirements [11]. The SOP user web app makes recommendations based on the information presented in this paper and the criteria set by the SOP developer. It empowers the forensic practitioner, whether working at the crime scene or in the laboratory, to make informed choices between fibre recovery options, thereby facilitating both validation compliant practice and optimal fibre recovery. Readers interested to know more about these web apps are encouraged to contact the corresponding author.

2. Materials and methods

This study was designed using the recommendations for validation studies as described in the Forensic Science Regulator's Codes of Practice and Conduct [11].

2.1. Samples

2.1.1. Target fibres

The target fibres chosen for this study were cylindrical polyester fibres from a high-visibility vest, which fluoresced when illuminated with a hand-held LED torch (i.e. flashlight) that emits light at 395nm.

2.1.2. Surfaces

To simulate casework, a list of common surfaces encountered at

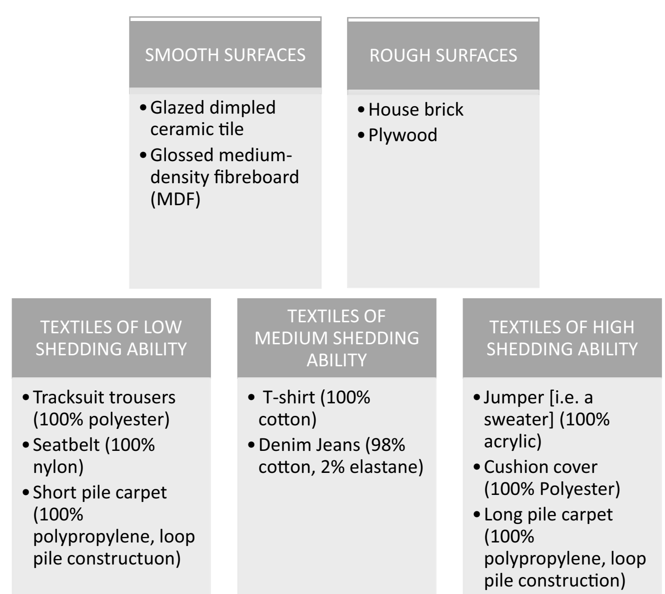

Fig. 1. The twelve test surfaces, categorised by surface roughness or shedding ability.

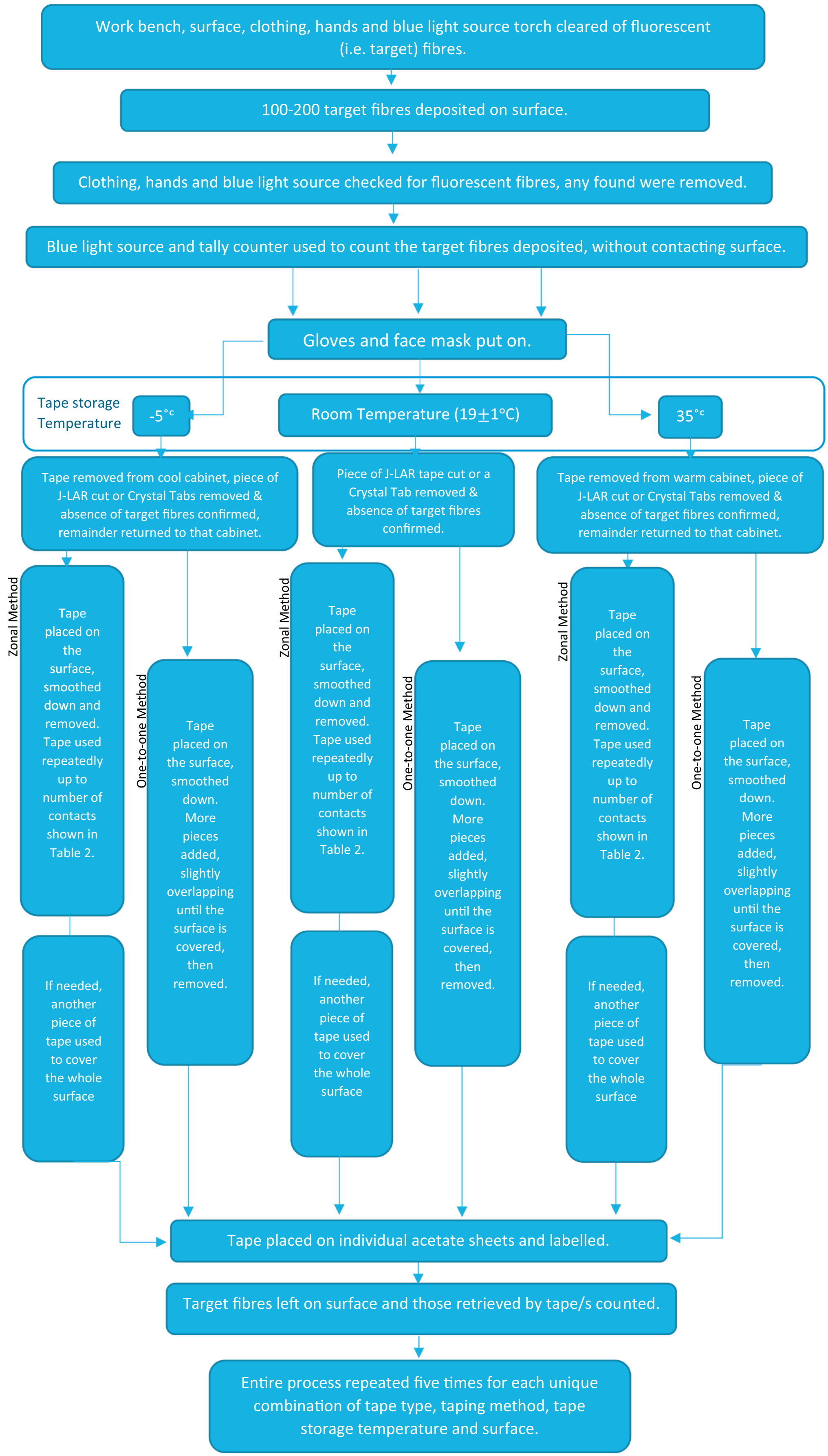

Fig. 2. The experimental procedure.

Table 2
The maximum number of contacts for each piece of tape used in the zonal method for each of the unique combinations of the experiment's independent variables.

Surface type	Maximum number of times the tape was used on a designated surface at each storage temperature					
	−5 °C		19 ± 1 °C		35 °C	
	J-LAR	Crystal Tabs	J-LAR	Crystal Tabs	J-LAR	Crystal Tabs
Plywood	5	5	5	5	5	5
Glossed MDF	5	5	5	5	5	5
Ceramic tile	5	5	5	5	5	5
Short carpet	5	5	4	4	5	5
Long carpet	3	3	2	2	3	3
Cushion cover	3	3	3	3	2	2
Brick	4	4	3	3	4	4
Tracksuit trousers	5	5	5	5	5	5
T-shirt	5	5	5	5	5	5
Jumper	4	4	4	4	4	4
Jeans	5	5	5	5	5	5
Seatbelt	5	5	5	5	5	5

crime scenes was provided by Warwickshire & West Mercia Police. Twelve representative surfaces were chosen from that list for this study. These twelve were then categorised by texture and, for textile fabrics, shedding ability (Fig. 1). An area of 338.2 cm^2 was either cut or isolated on each surface bar one. The one exception was the brick surface, which was 219.3 cm^2. For the brick, the roughest side was used as the test surface. For all surfaces – bar the tracksuit trousers, T-shirt, jeans and jumper – a grid was drawn on each surface with a suitable pen. This was done to aid the subsequent counting of target fibres and provide reassurance that none were missed or double counted. Throughout the study, the surfaces were kept clean and dry. None of the surfaces produced fluorescence visible to the naked eye when illuminated with the LED torch referred to in Section 2.1.1.

2.1.3. *Tapes*

The following tape types were used:

- J-LAR – purchased from Tetra Scene of Crime and/or CSI Equipment Ltd;
- Crystal Tabs – obtained from Warwickshire & West Mercia Police.

(Note that WA Products sell both J-LAR [Product No. B20610] and Crystal Tabs [Product No. B20633], which is where Warwickshire & West Mercia Police buy them from).

2.2. *Experimental procedure*

For each repeat determination of the fibre retrieval rate, between 100 and 200 target fibres were deposited onto the surface from which they were to be tape lifted. Prior to this deposition, the source of these fibres (the high-visibility vest) was abraded with coarse sandpaper to aid fibre transfer. Three deposition techniques were used: rubbing (multiple contacts, with the donor fabric being moved reciprocally across the surface a maximum of five times), touching (placing of the donor fabric directly onto the surface with the application of light pressure but without moving it across the surface) and scraping (the use of sandpaper to scrape the donor fabric above the surface, allowing fibres to transfer). During the rubbing and touching techniques, care was taken to use the same hand pressure for each deposition. Rubbing was used for the jumper, carpets, cushion cover, jeans, T-shirt and tracksuit trousers. Touching was used for the brick. When rubbing or touching was employed, and fewer than 100 fibres were transferred to the test surface, scraping was then used until the desired number of fibres (i.e. 100 to 200) was transferred to the surface concerned. Scraping was used as the sole technique for the seat belt, plywood, glossed MDF and ceramic tile.

For each of the twelve surfaces, both J-LAR and Crystal Tabs were tested using both methods of taping (zonal and one-to-one). For each combination of surface type, tape type and taping method, three tape storage temperatures were tested (−5 °C, room temperature [19 ± 1 °C] and 35 °C). This therefore resulted in 144 unique combinations of the levels of these four independent variables (12 surfaces × 2 tape types × 2 taping methods × 3 temperatures). The testing for each of these combinations was repeated five times.

In all repeats, prior to use, the tape was stored – on the roll on which it was supplied – for a minimum of 24 hours in air of its designated temperature. Immediately before use, the rolls of tape stored at either −5 or 35 °C were moved from their temperature-controlled environments into one of 19 ± 1 °C. At which time an appropriate amount of tape was removed from the roll concerned and used, and the remainder was placed back into its former temperature-controlled environment. The tape stored at room temperature (19 ± 1 °C) was kept and used at this temperature throughout the experiment. A different roll of each tape type was used for each of the three storage temperatures studied.

The experimental procedure is represented in Fig. 2. During the entire process, the airflow around the testing area, and particularly the surface being tested, was kept to a minimum. Except when the target fibres were being added to any given surface, that surface was kept separate from the donor fabric and only the analyst and technician had access to the testing area during the experiment.

The pieces of tape used were each approximately 14 cm long, although slightly shorter pieces were used for the brick due to its relatively small sampling area. In all repeats, the tape was applied in the following manner. The tape was held in a U shape, adhesive side facing down, with the bottom of the U being placed on the surface and the sides being eased down until the tape was flat against the surface. One end of the tape was then pulled free of the surface and the whole tape was carefully smoothed across the surface using two fingers, without these touching the surface, before removing the tape. The surfaces being tested were cleared of fibres between repeats using a low linting paper towel, taping with J-LAR or Sellotape® and/or using tweezers. Prior to reuse, each surface was confirmed to be free of target fibres by using a violet light, in which they fluoresced.

For any given repeat of the zonal method, as many pieces of tape were used as needed to process the entire sampling area. Each of these pieces was applied multiple times up to the maximum shown in Table 2. Each such application was on a different portion of the sampling area. This maximum prevented overloading of the tape or reduction of adhesive efficacy. The maximum number of times each of J-LAR and Crystal Tabs could be used on each surface at each storage temperature before becoming overloaded was identified by qualitative observation prior to the main experiment.

When using the one-to-one method, each piece of tape was contacted with the surface once only. For each repeat, the entire test surface was covered with six pieces of tape, with slight overlap between neighbouring pieces to ensure complete coverage. For all surfaces, the tapes were removed in reverse order to their placement. For consistency's sake, a specific order and pattern of tape placement was used for each repeat on any given surface.

Irrespective of the method used, after its contact with the surface for the last or only time, each piece of tape was adhered to a separate clean acetate sheet. This was then labelled with details of the tape storage temperature, repeat number, tape number, surface and taping method. For each repeat, the target fibres on each tape and those left on the test surface were then counted using light from the torch mentioned in Section 2.1.1 to aid fibre visualisation and a tally counter. Counting was systematic to avoid missing fibres or double counting, starting at the top left-hand side of the tape and working left to right and from top to

Table 3
The mean and median fibre retrieval rates seen.

J-LAR (% Retrieval. For each mean and median, n = 5)

SURFACE	ZONAL TAPING -5°C Mean ($\bar{x}$)	Rating	Median	ZONAL TAPING 19°C Mean ($\bar{x}$)	Rating	Median	ZONAL TAPING 35°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING -5°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING 19°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING 35°C Mean ($\bar{x}$)	Rating	Median
Plywood	98.6	****	99.1	92.9	****	92.8	98.5	****	100.0	99.3	****	99.3	98.7	****	99.3	99.5	****	99.5
Glossed MDF	97.9	****	97.4	93.1	****	96.9	99.7	****	100.0	99.3	****	99.4	97.7	****	97.7	99.3	****	99.4
Ceramic tile	98.1	****	98.0	95.2	****	95.5	97.9	****	98.3	98.9	****	98.7	98.9	****	99.2	99.7	****	100.0
Short carpet	83.3	***	84.8	75.0	**	69.4	80.2	***	79.5	92.2	****	92.2	84.0	***	88.8	85.9	***	84.1
Long carpet	83.2	***	84.0	77.9	**	75.1	83.6	***	80.5	82.5	***	83.7	81.0	***	80.9	84.6	***	84.0
Cushion cover	73.2	**	74.8	56.9	*	62.3	85.7	***	85.4	86.7	***	88.0	80.4	***	82.8	84.3	***	82.4
Brick	88.6	***	90.2	92.4	****	93.0	93.9	****	95.4	93.0	****	92.7	92.2	****	92.8	95.9	****	95.7
Tracksuit trousers	91.5	****	90.6	77.4	**	81.0	92.8	****	92.2	95.3	****	96.6	86.0	***	87.3	94.8	****	95.1
T-shirt	95.0	****	96.0	72.3	**	72.3	94.3	****	95.1	94.0	****	94.3	92.4	****	94.7	95.4	****	96.4
Jumper	71.3	**	76.4	71.1	**	67.7	89.2	***	88.3	90.9	****	91.5	85.5	***	86.9	92.9	****	94.0
Jeans	86.7	***	86.6	58.6	*	54.6	90.8	****	91.7	86.2	***	86.4	89.3	***	88.6	90.1	****	92.5
Seatbelt	89.7	***	90.1	89.4	***	89.1	92.8	****	94.0	94.4	****	94.7	96.4	****	97.0	95.9	****	96.1

CRYSTAL TABS (% Retrieval. For each mean and median, n = 5)

SURFACE	ZONAL TAPING -5°C Mean ($\bar{x}$)	Rating	Median	ZONAL TAPING 19°C Mean ($\bar{x}$)	Rating	Median	ZONAL TAPING 35°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING -5°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING 19°C Mean ($\bar{x}$)	Rating	Median	ONE-TO-ONE TAPING 35°C Mean ($\bar{x}$)	Rating	Median
Plywood	99.8	****	100.0	99.1	****	98.6	99.6	****	100.0	99.7	****	100.0	99.5	****	99.4	99.9	****	100.0
Glossed MDF	99.5	****	99.4	100.0	****	100.0	100.0	****	100.0	100.0	****	100.0	99.8	****	100.0	100.0	****	100.0
Ceramic tile	99.7	****	100.0	99.6	****	100.0	99.4	****	99.4	99.7	****	100.0	99.6	****	100.0	99.3	****	99.3
Short carpet	95.4	****	95.7	88.7	***	88.4	94.9	****	95.4	91.8	****	92.4	84.3	***	81.3	92.6	****	92.3
Long carpet	91.7	****	90.9	83.9	***	83.9	84.4	***	83.3	86.1	***	88.3	84.8	***	88.3	83.7	***	82.4
Cushion cover	83.4	***	82.7	87.4	***	90.3	89.9	***	89.7	91.9	****	91.0	92.0	****	93.4	87.3	***	85.5
Brick	97.9	****	98.2	94.3	****	95.3	96.2	****	96.6	98.3	****	98.2	99.3	****	99.3	96.6	****	96.8
Tracksuit trousers	95.0	****	94.6	94.9	****	94.6	94.5	****	94.9	96.2	****	96.0	95.4	****	95.5	96.3	****	96.1
T-shirt	92.0	****	91.3	90.5	****	90.7	93.4	****	93.7	95.4	****	96.1	94.3	****	93.5	97.8	****	98.6
Jumper	85.7	***	87.9	86.9	***	86.7	83.9	***	83.3	89.2	***	90.6	85.1	***	85.3	83.9	***	84.8
Jeans	91.7	****	92.3	84.6	***	85.3	95.4	****	95.5	95.4	****	96.4	80.9	***	81.8	94.5	****	93.3
Seatbelt	91.2	****	91.5	93.3	****	93.1	94.1	****	93.1	94.9	****	94.4	99.5	****	99.3	95.9	****	95.4

Key,

Range of $\bar{x}$	Rating
$\bar{x} < 70$	*
$70 \le \bar{x} < 80$	**
$80 \le \bar{x} < 90$	***
$90 \le \bar{x} \le 100$	****

bottom.

2.3. Statistical analysis

A balanced four-way factorial ANOVA model was built in which reflected log fibre recovery rate was the dependent variable and the independent variables (i.e. factors) were tape type, tape storage temperature, application method and the surface from which the target fibres were retrieved. This model included all main effects and all interaction terms. There were no missing data and the whole data set was included in the analysis. The threshold for significance (i.e. alpha) was set at 0.05 and effect size was measured using partial eta squared.

This was followed by four sets of simple effects tests, one set for each of the four independent variables. In each of these sets, one test was carried out for each of the unique combinations of the levels (i.e. values) of the factors other than the one under consideration. For example, when considering tape type, a set of 72 simple effects tests was carried out. That is one test for each unique combination of storage temperature (there were three of these temperatures), application method (two of these) and surface (12 of these). In this paper, any given unique combination of factor levels is referred to as a condition.

Each of these sets was considered to be a family. Therefore, with in each set, adjustment was applied to the p values to control the family wise error rate. Bonferroni correction was used to make these adjustments. It was also recognised that the four sets of simple effects tests were all in one family. In recognition of this, two alpha levels were set, one at 0.05 and the other at 0.0125 (i.e. 0.05/4). For any given simple effect test, the following rules were used when deciding significance: if adjusted $p > 0.05$ then *not significant*, if $0.05 \geq$ adjusted $p > 0.0125$ then *discussable* and if adjusted $p \leq 0.0125$ then *significant*. The discussible adjusted p values represent those tests that would have shown significance if only one, and not four, sets of simple effects tests had been conducted.

The simple effects tests referred to above are sufficient to establish which of the two levels of the tape types factor (J-LAR and Crystal Tabs) are more efficient at retrieving fibres for each of the conditions under test. The same is true of the two levels of the application method factor (zonal and one-to-one). However, this is not the case for the levels of the factors temperature and surface, as these factors have more than two levels each.

Therefore, for each of the factors with more than two levels, pairwise contrasts were conducted after the simple effects tests had been completed. When doing so, only those contrasts which had corresponding simple effects that were either significant or discussible were considered. The p values for these contrasts were adjusted using the Tukey HSD correction to conserve the family wise error rate. For each of the two factors for which this method was employed, this correction was applied based on 144 means and the residuals' degrees of freedom (i.e. 576).

If, in any one of the significant differences found in the pairwise contrasts, the corresponding simple effect had been found to be in the discussable range, that pairwise difference was also labelled as discussable.

In the simple effects tests and pairwise contrasts, r was used to gauge effect size.

All of the statistical analysis was carried out with RStudio Desktop Open Source Edition version 1.0.143 [15] using R version 3.4.1 [16] and the following R packages: car version 2.1-5 [17], fpc version 2.1-10 [18], lsmeans version 2.27-2 [19], multcompView version 0.1-7 [20], phia version 0.2-1 [21] and sjstats version 0.11.1 [22]. Parallel coordinate plots were created using version 0.3.0 of the parcoords package for R [23], which is founded in the work led by Chang [24], building on that of Inselberg [25]. The exact goodness of fit tests referred to in Section 4.5 were carried out using the multinormal.test() function from version 1.1 of the EMT package [26].

All the raw data and the script used in its analysis are available elsewhere [27].

Readers who are unfamiliar with the statistical methods used may find useful introductions in the books by Field, Miles and Field [28], and Clark-Carter [29], and the vignette for the phia R package [30]. Similarly, those wishing to acquaint themselves with the R statistical programming language might find it helpful to read the books by Kabacoff [31] and Matloff [32], the former of which has a very useful website [33].

3. Results

Table 3 shows the mean and median percentage fibre retrieval rates of the five repeat determinations that were conducted for each of the 144 unique factor level combinations in this experiment. This Table also contains a star rating system which categorises the mean fibre retrieval rates seen. This allows the identification of those taping methods and tape types that were found to be effective in this study for each surface and tape storage temperature used. It also allows easy comparison of the data within this study. In this system, a four-star rating denotes excellent mean retrieval rates ($90\% \leq \bar{x} \leq 100\%$), three-star shows very good mean retrieval rates ($80\% \leq \bar{x} < 90\%$), two-star depicts good mean retrieval rates ($70\% \leq \bar{x} < 80\%$) and one-star indicates mean retrieval rates of $\bar{x} < 70\%$. The last of which is considered to be a risk area. The choice of the ranges that correspond with these ratings was informed by previous research [5,9,34 and 35] and the acceptance criteria set by Warwickshire & West Mercia Police.

Across all tape storage temperatures, surfaces and taping methods, the range of mean fibre retrieval rates for Crystal Tabs and J-LAR were 80.9%–100% and 56.9%–99.7%, respectively.

The range of mean percentage fibre retrieval for the zonal method across all tape storage temperatures, surfaces and tape types is 56.9%–100%. That of the one-to-one method is 80.4%–100%.

The mean percentage retrieval of fibres from each surface for both J-LAR and Crystal Tabs indicate that surface type effects the efficiency of the tape. Generally, it can be stated that the smoother and less sheddable surfaces had higher mean retrieval percentages than the rougher and more sheddable ones. This observation is explored further in Section 4.6.

Figs. 3 to 6 respectively show notched box plots of fibre retrieval rate (i.e. efficiency) data grouped by each of tape type, tape storage temperature, taping method and surface. It is noteworthy that the box plots in these Figures illustrate that the efficiency data for each of the levels of the four factors studied here have a pronounced negative skew.

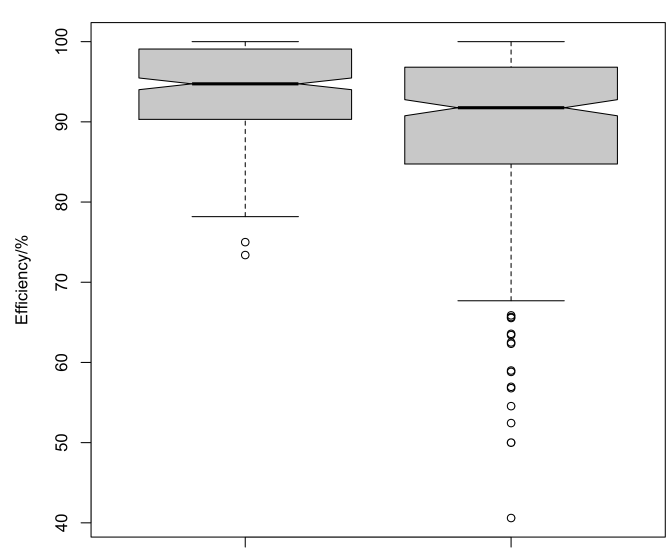

Fig. 3. Notched box plots of efficiency grouped by tape type.

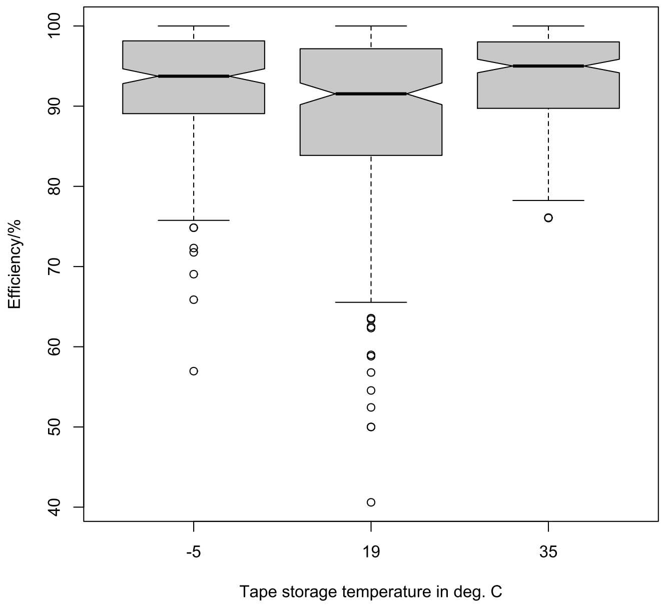

Fig. 4. Notched box plots of efficiency grouped by tape storage temperature.

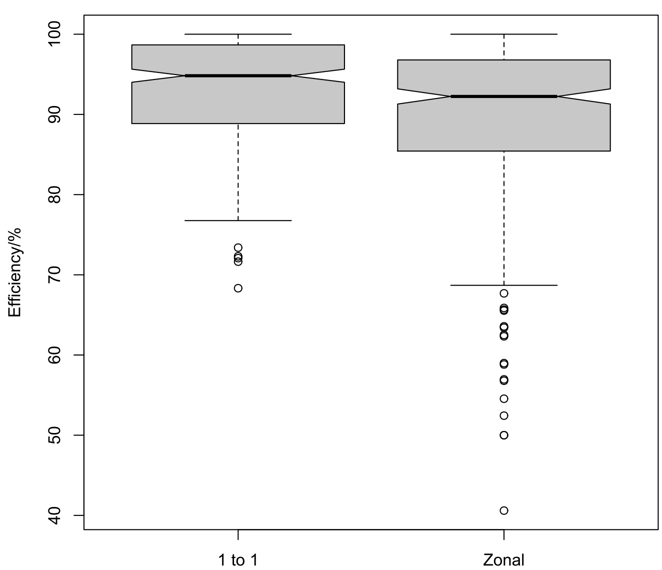

Fig. 5. Notched box plots of efficiency grouped by taping method.

This indicates that for raw efficiency data, median would be a better measure of central tendency than mean and that interquartile range would be a more meaningful measure of spread than standard deviation.

Within each of Figs. 3 to 6, those notches which do not overlap between two box plots provide strong evidence of differences between medians [36, p62]. On this basis and setting aside any interaction effects, the data suggests that:

- Crystal Tabs tends to be more efficient than J-LAR;
- tapes stored at 35 °C, and possibly those stored at −5 °C, tend to outperform the efficiency of those stored at 19 ± °C;
- one-to-one taping tends to retrieve more of the fibres from a surface than zonal taping.

However, great caution should be exercised when using these observations to inform crime scene practice as they ignore both the interactions between the factors under study (tape type, tape storage temperature, taping method and surface) and the effect of factors, such as ease of use, which do not form part of this quantitative work. Further consideration is given to interactions between tape type, tape storage temperature, taping method and surface in Section 4 and a commentary on the varying propensity for tape to tear and variation in its pliability when stored at different temperatures is provided later in this section (i.e. Section 3).

Fig. 6 suggests that the effect of surface is complex but that it may be possible to categorise surfaces into different clusters based on a combination of median and interquartile range efficiency data. This is explored further in Section 4.6.

Figs. 7 and 8 are dot plots showing the median and interquartile ranges of efficiency for each combination of surface, taping method and tape storage temperature for Crystal Tabs and J-LAR respectively. In each case, these are ordered from most (top) to least efficient as measured by median efficiency. These suggest that, during the experiment under consideration, Crystal Tabs tended to outperform J-LAR but that this is not true for all the combinations of surface, taping method and tape storage temperature that were studied. See Section 4 for a detailed examination of this and other trends present in the data.

Parallel coordinate plots offer a convenient method for the display and exploration of complex multivariate data [25]. Various interactive parallel coordinate plots have been created from the data generated by the study reported here and are available on line [27,37]. Fig. 9 shows screenshots of one such plot. It depicts how the median and interquartile range efficiency data varies with the experimental factors of this study. The left-hand panel of that Figure shows the entire data set, whilst that on the right demonstrates how the user can use the interactive version of the plot [27[2]] to apply filters to isolate parts of the dataset. In this case, such application has allowed the user to see that, when stored and used at room temperature (19 ± 1°*C*), using a zonal method of application to a jumper, Crystal Tabs outperformed J-LAR in terms of improved efficiency and decreased interquartile range. Clearly, this does not indicate whether any such difference in performance is statistically significant. This is a matter that is explored in Section 4.

Although not a quantitative part of this study, it was noted that the storage temperature of the tape did have an influence on the ease of use of J-LAR. When stored at −5 °C, on removal from the roll, that tape was more susceptible to ripping than when it had been stored at either 19 ± 1 °C or 35 °C, resulting in wasted tape. When stored at −5 °C, this tape type was also much more prone to ripping when removing it from other pieces of tape during the one-to-one method. In contrast, when stored at 35 °C, J-LAR was seen to be much easier to remove from other tapes during that method than when it was stored at either 19 ± 1 °C or −5 °C.

Crystal Tabs, at any of the storage temperatures, did not rip when pulled either from other pieces of tape during the one-to-one method or from its backing. When stored at 35 °C, Crystal Tabs was seen to be more pliable than when stored at either of the other two storage temperatures and therefore easier to bend around surfaces, especially the brick.

Whilst outside the remit of this study, the authors note that they observed by eye (using white, non-polarised light) that the Crystal Tabs and J-LAR that was used:

- exhibited equivalent optical clarity under the microscope;
- did not incur any noticeable discolouration after two years' storage in a cardboard box in a laboratory environment out of direct sunlight.

[2] The interactive version of the plot shown in Fig. 9 is available as the last of the plots given in the html file in the initial data description folder that can be accessed via [27].

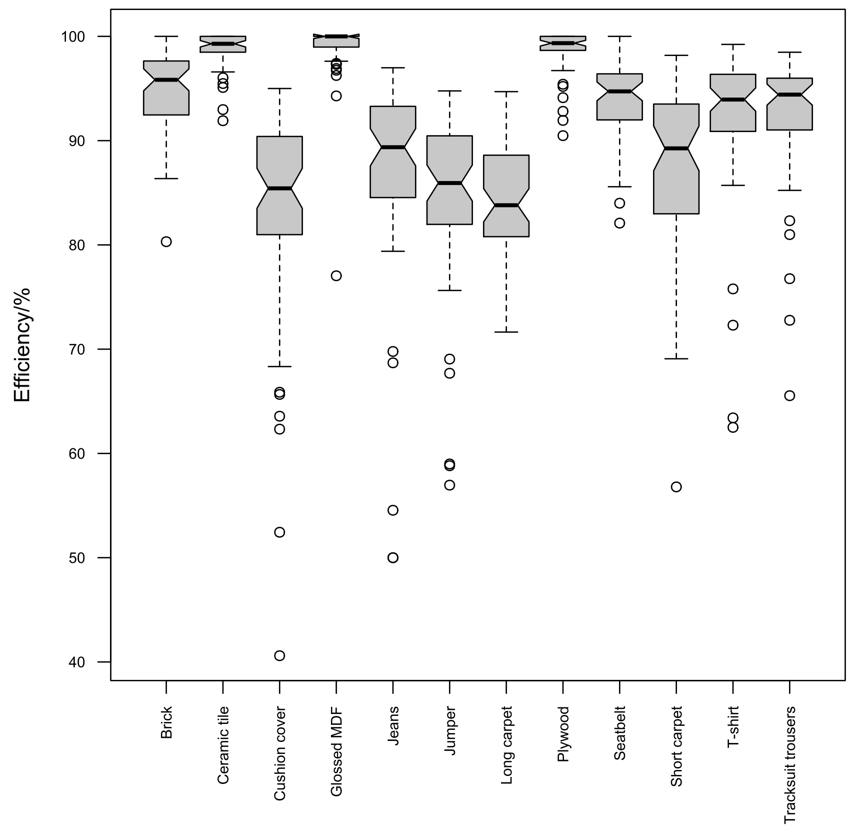

Fig. 6. Notched box plots of efficiency grouped by surface.

4. Discussion

4.1. Comparison with previous studies

Overall, the mean percentage fibre retrieval rates (i.e. efficiencies) seen in this study were consistently higher than those reported in previous literature.

Lowrie and Jackson [38] have reported a study in which three different fibre types (wool, acrylic and cotton) were donated to three different garments (wool jumper, acrylic jumper and polyester jacket) that were then worn for 8h each. After this, fibres were retrieved by zonal taping with Sellotape® (tape storage temperature was not specified). Mean fibre retrieval rates (n = 3) ranging from 30.3% to 49.5% were reported from the acrylic jumper used in that study. The mean retrieval rates observed in the study reported here from the acrylic jumper for all unique combinations of tape type, tape storage temperature and taping method range from 71.11% to 92.90%. These data are each the mean of five repeat determinations and are noticeably higher than the largest mean retrieval rate from the acrylic jumper that was reported by Lowrie and Jackson. In their report, Lowrie and Jackson state that "*It has been shown … that after 8 h wear those fibres remaining on garments are fairly few in number and tightly bound by mechanical forces to the recipient garment.*". From which may be inferred that those fibres which are more loosely bound, and which do not become tightly bound during wear, are those which are lost during that activity. In the study reported here, there was no period of wear between the addition and retrieval of the donor fibres, so any that were loosely adhered would still be present when the tape was applied. It seems likely that such fibres are readily removed by tape lifting, explaining the difference in retrieval rates seen between the Lowrie and Jackson study and the one reported here.

Wael, Gason and Baes [5] reported mean (n = 4) retrieval rates of 23.5%–61.0% of seeded fibres from textile chairs. Of the surfaces used in the study reported here, the long-pile carpet seems to be the most similar to that employed in that previous study. The mean retrieval rates produced for the long-pile carpet, for all 12 unique combinations of tape type, tape storage temperature and taping method range from 77.86% to 91.72%, all of which are much higher than those reported in that previous study. In the study reported here, the lowest retrieval rate of target fibres from the long-pile carpet for an individual repeat measurement was 71.64% which is, again, larger than the highest mean rate reported by Wael, Gason & Baes [5]. Differences between the two studies in the techniques used to transfer the target fibres to the surfaces under consideration could, in part at least, be responsible for the difference in the retrieval rates seen. The seeding transfer approach used by Wael *et al.*, in which individual target fibres were each partially inserted beneath warp threads with tweezers [5], may have led to target fibres being more tightly bound within the weave of the recipient fabric than the transfer methods used in the study reported here (see Section 2.2 for details).

As explored further in Section 4.6, in this study, surface type has been found to influence the efficiency of fibre recovery. A categorisation of the surfaces concerned is provided in Fig. 1 and Figs. 6 to 8 display the efficiency with which target fibres were retrieved from them by the tapes used. From this it can be seen that, typically, the smoother and/or less sheddable surfaces produced higher fibre recovery rates than did rougher and/or more sheddable ones. A possible explanation is that the target fibres were more firmly adhered to the rougher surfaces due to their textured or textile-based nature. The sheddabilty of textile surfaces could also be a contributing factor, as the background fibres from those surfaces could interfere with the retrieval of the target fibres. Research carried out by Lowrie & Jackson [38] observed that a smooth polyester garment gave the highest retrieval rate compared to a rough-surfaced wool garment and a smooth-surfaced acrylic garment. In essence, that previous observation is consistent with the relevant findings of the study reported here. Fig. 6 summarises those findings

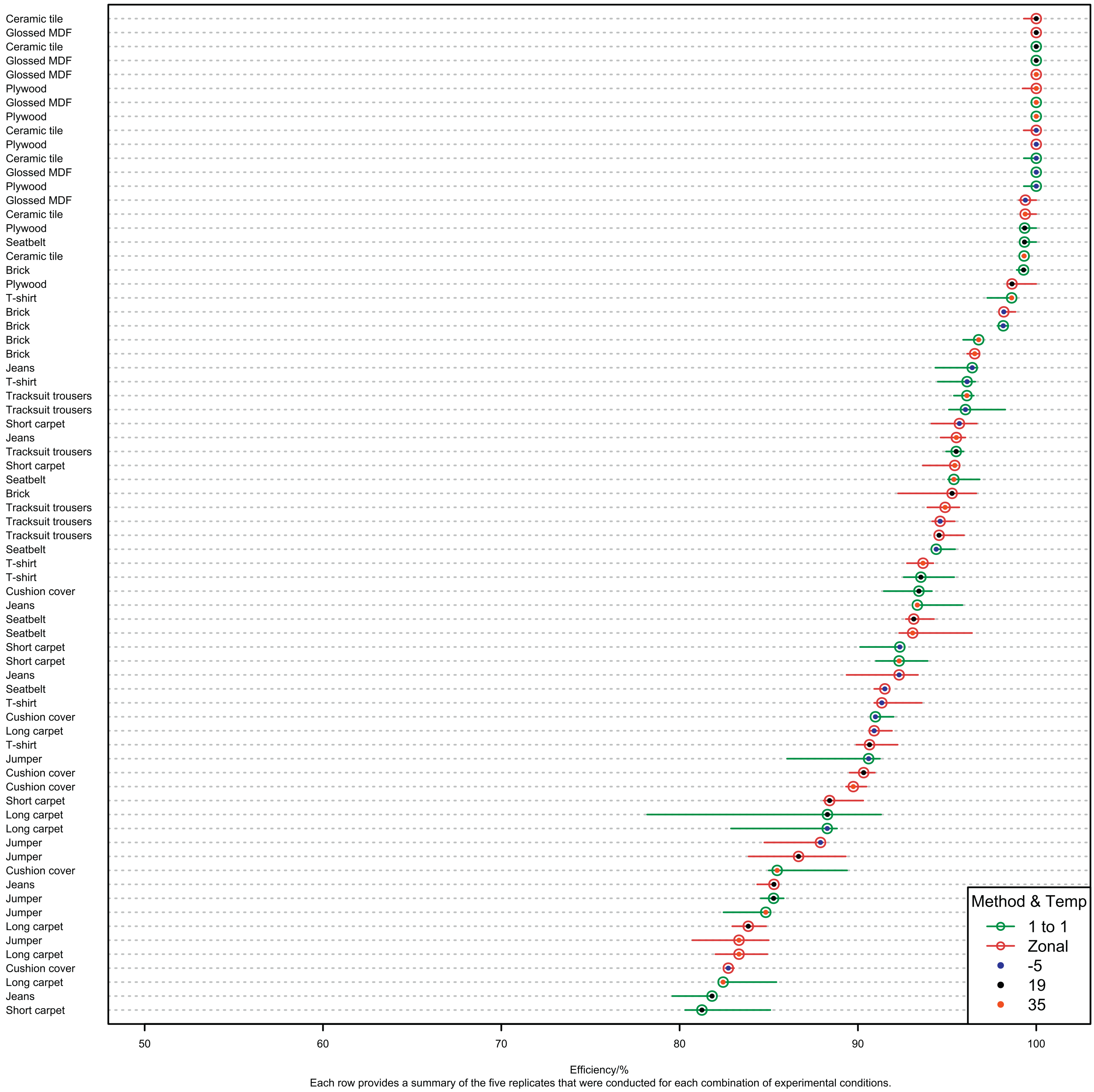

Fig. 7. A dot plot showing the median and interquartile ranges of efficiency for each combination of surface, taping method and storage temperature tested using Crystal Tabs.

and provides evidence that the overall median target fibre retrieval rate from the smooth polyester tracksuit trousers exceeded those for each of all the other textile surfaces except the seatbelt and the smooth cotton T-shirt. The finding of the latter of these two exceptions (a surface not studied by Lowrie & Jackson [38]) is essentially consistent with the findings of Schotman & van der Weerd [9], as, in their study there was some overlap between the retrieval rates of polyester target fibres on cotton fabric and of such target fibres on polyester fabric. Although, in their study with polyester target fibres, cotton fabric produced, on average ($\bar{x}$ = 97.4%, n = 3), higher retrieval rates than did polyester fabric ($\bar{x}$ = 96.0%, n = 3).

It is common practice to store basic crime scene equipment, such as lifting tapes, inside crime scene investigators' vehicles [10]. During this storage, the tape's temperature will track that of its environment; thus, the tape temperature will vary with geographical location, and time of day and year. The tape storage temperatures chosen for this study (−5, 19 ± 1 and 35 °C) were selected to encompass the typical range of temperatures encountered across the year in the UK. As of the time of writing (19 December 2017), there is no previous research reported in the literature on the effect of tape storage temperature on usability in the forensic context, whether for lifting fibres or other evidence (such as fingermarks).

4.2. ANOVA

The experiment reported here has a balanced four-way factorial

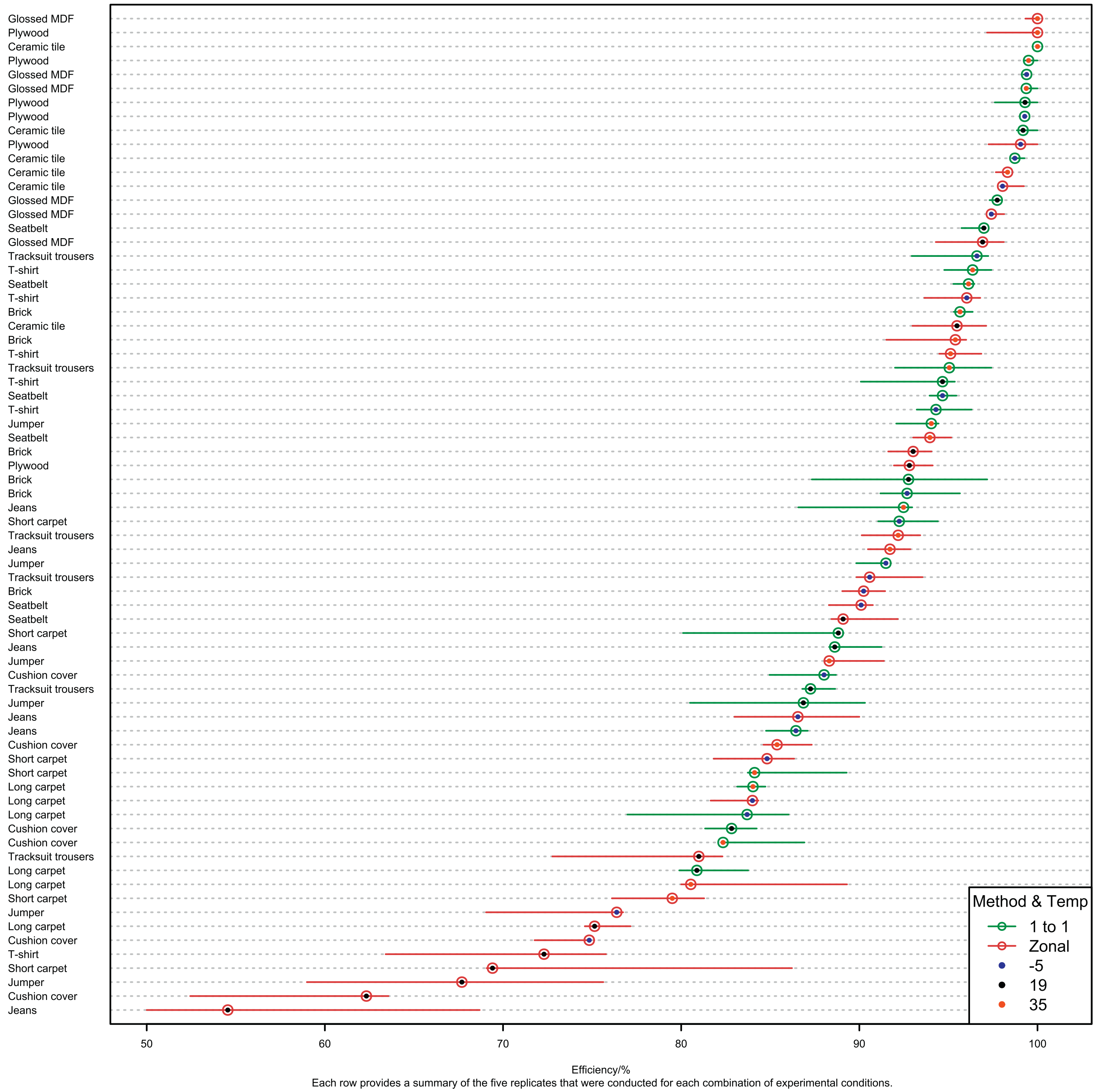

Fig. 8. A dot plot showing the median and interquartile ranges of efficiency for each combination of surface, taping method and storage temperature tested using J-LAR.

ANOVA design, meaning that it has:

- one dependent variable, namely the percentage of target fibres retrieved (i.e. the efficiency);
- four categorical independent variables (i.e. factors), namely tape type (known as Tape), tape storage temperature (Temp), taping method (Method) and the surface from which the target fibres were retrieved (Surface);
- the same number of repeat determinations (namely five in this case) of the dependent variable at each of the unique combinations of the individual variants (i.e. levels) of the factors. (As detailed in Section 2, Tape, Temp, Method and Surface have two, three, two and 12 levels respectively – producing 144 unique level combinations and a total of 720 efficiency determinations.)

The pronounced negative skew that is present in the efficiency data precluded the use of ANOVA on those raw data. A reflected logarithmic transformation was therefore used. The resulting dependent variable (reflected log efficiency) has an inverse relationship with the efficiency data on which it is based.

Using reflected log efficiency as the dependent variable, a four-way factorial ANOVA model was built based on all main effects and interactions and using the entire data set. Post-model diagnostics revealed the following:

- The normal quantile-quantile plot shown in Fig. 10. Arguably, this

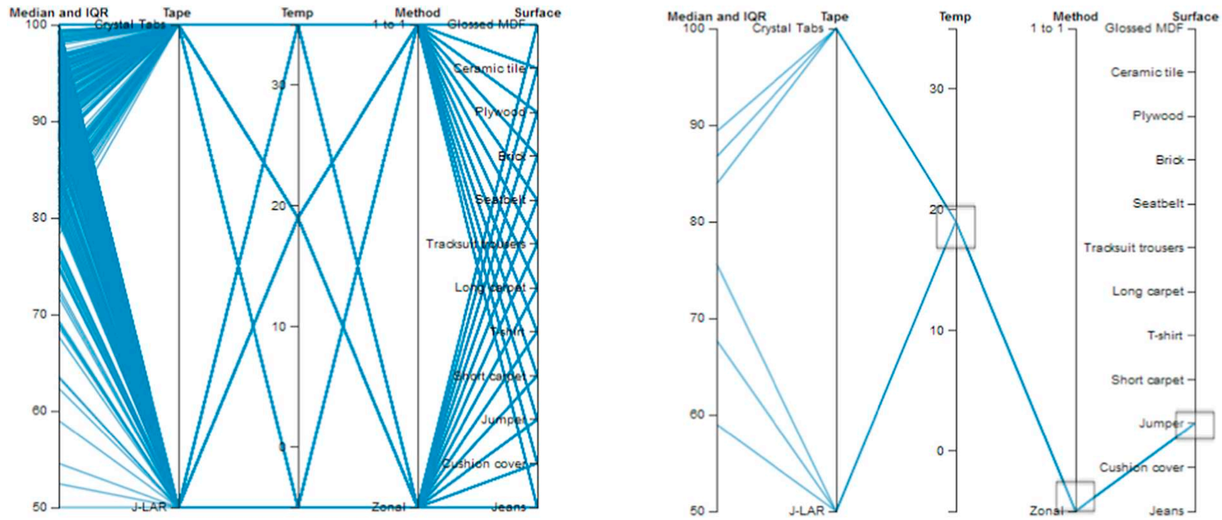

Fig. 9. Screenshots of the parallel coordinate plot that shows the median and interquartile range efficiency data for all the unique combinations of the four factors under consideration. The screenshot o n the left shows the full data set whilst that on the right gives an example of the application of user-defined filters.

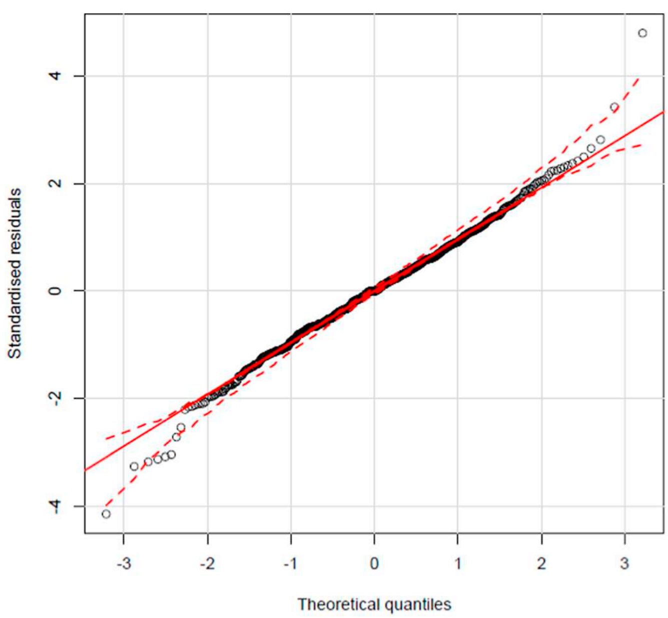

Fig. 10. Normal Q-Q plot with approximate 95% confidence envelope.

reveals that all bar 10 (i.e. 1.4%) of the 720 data points are in very good agreement with what would be expected from normally distributed data.

- A non-significant outcome for a Kolmogorov-Smirnov test of normality of the residuals (D = 0.032261, p = 0.4419). (However, there are ties present (8.3% of the data)).
- A significant outcome for a Shapiro-Wilk normality test applied to the residuals (W = 0.99188, p = 0.0005581).
- A significant outcome for a Levene's Test for homogeneity of variance with the centre set to mean (F = 2.3539, $p = 1.092 \times 10^{-12}$).
- A non-significant outcome for a Levene's Test for homogeneity of variance with the centre set to median (F = 0.9641, p = 0.5981). (This is a more robust version of the Levene's test that is referred to above).

From the above it would seem that there is a small deviation from the normality assumption. For the sake of preserving the balanced design, outliers were not removed from the data. The above also reveals a deviation from the homogeneity of variance assumption. However, this deviation would seem to be small – especially in light of the experiment's balanced design. On this basis, the authors decided to proceed with the ANOVA model.

The findings of this model are summarised in Table 4. From which it can be seen that all four main effects and all interactions bar

Table 4
ANOVA summary

Term	Degrees of freedom	F	p	Partial eta squared	Significant at > 95% confidence	Effect size magnitude
Tape	1	285.580	0.000	0.331	Yes	> large
Temp	2	61.408	0.000	0.176	Yes	> large
Method	1	136.764	0.000	0.192	Yes	> large
Surface	11	345.759	0.000	0.868	Yes	> large
Tape:Temp	2	28.099	0.000	0.089	Yes	medium-large
Tape:Method	1	23.153	0.000	0.039	Yes	small-medium
Temp:Method	2	15.485	0.000	0.051	Yes	small-medium
Tape:Surface	11	6.320	0.000	0.108	Yes	medium-large
Temp:Surface	22	6.128	0.000	0.190	Yes	> large
Method:Surface	11	4.206	0.000	0.074	Yes	medium-large
Tape:Temp:Method	2	2.589	0.076	0.009	No	< small
Tape:Temp:Surface	22	4.025	0.000	0.133	Yes	medium-large
Tape:Method:Surface	11	3.712	0.000	0.066	Yes	medium-large
Temp:Method:Surface	22	2.504	0.000	0.087	Yes	medium-large
Tape:Temp:Method:Surface	22	3.158	0.000	0.108	Yes	medium-large
Residuals	576					

Tape:Temp:Method were found to be significant at a confidence level of greater than 95%. The last column of Table 4 provides a categorisation of the effect size using 0.0099, 0.0588 and 0.1379 as the cut points between small, medium and large effect sizes [39]. This provides evidence that all the significant terms are also substantive in their effects.

Full details of the code used to build the ANOVA model used and test its assumptions are available in the public domain [27].

Noting the statistical significance of the Tape:Temp:Method:Surface interaction and applying the principle of marginality [30], it is necessary to explore that interaction effect in order to understand the interplay between the effects of the factors in this experiment. Indeed, according to that principal, the presence of the significant Tape:-Temp:Method:Surface interaction means that the lower order interactions and main effects that it contains should neither be tested nor interpreted [30]. In this work, a simple effects approach to the testing and interpretation of the interplays present in the Tape:Temp:Method:Surface interaction has been adopted for each of the factors in that interaction. The outcome of this is explored in Sections 4.3, 4.4, 4.5 and 4.6.

4.3. Effect of tape type

A simple effects analysis was carried out which examined the effect of tape type on the mean reflected log efficiency at each of the 72 unique combinations (i.e. conditions) of tape storage temperature, taping method and surface. During this analysis, the Bonferroni adjustment was used to control the familywise error rate. It revealed that during the experiment, in 61 of these 72 conditions (i.e. 84.7%), Crystal Tabs out-performed J-LAR and in the remaining 11 conditions, the reverse was true.

The advantage of the simple effects analysis is that it allows differentiation between those conditions that showed either statistically significant or discussable differences in performance and those which did not. Table 5 summarises the other key findings of that analysis. The column labelled 'Difference …' in that Table shows the value of the mean reflected log efficiency of the Crystal Tabs tape minus that of the J-LAR tape. To save space, only those 17 conditions (23.6% of the total) for which this difference is either significant or discussable at a confidence level of > 95% are shown (the full version of Table 5 is given in this paper's Supplementary Materials and the R script used to create it is available elsewhere [27]). For each of these 17 statistically significant or discussable results, the entry in the 'Difference …' column is < 0. This shows that for all these 17, Crystal Tabs tape outperformed J-LAR and that none of the 11 instances in which J-LAR outperformed Crystal Tabs are statistically significant or discussable. This is consistent with the box plots shown in Figure 3, which indicate that, typically, overall, Crystal Tabs was more efficient at fibre retrieval than was J-LAR under the conditions of the study. As shown in Table 5, the effect sizes for the significant and discussible differences, as measured by r, all fall into the small to medium range (this is based on the following benchmark values for r: small = 0.10, medium = 0.30 and large = 0.50 [40, pp 79–81]). Interestingly, all three storage temperatures, both taping methods and all surfaces bar two (long carpet and jumper) are represented amongst the data presented in that Table.

An interactive parallel coordinate plot showing the full results of the simple effects analysis of the effect of tape type is available [37]. Screen shots from that plot are given in Fig. 11. Fig. 11(a) shows the entire dataset whilst Fig. 11(b) and (c) are screen shots after user-defined filters have been applied. In Fig. 11(b) these filters have isolated those surfaces that produced significant differences between the tape types when these tapes were stored at room temperature (19$^{\circ}C$) and applied using the zonal method. It also shows the range of the absolute difference between the reflected log efficiencies seen under these conditions and the range of values of effect size as measured by r that are associated with these differences. Part (c) illustrates how the plot could be used to inform crime scene practice. Faced with a plywood surface, a forensic strategy that expects the use of zonal taping and tapes that have been stored at room temperature, the user can apply the filters to isolate these conditions on the plot and check whether there is a significant difference in the performance of the tape types. In the case in question, the plot shows that Crystal Tabs outperforms J-LAR, that this difference is statistically significant, that the absolute difference in reflected log efficiencies seen was slightly greater than 1.5 and that effect size, as measured by r, is between 0.25 and 0.30. This information, together with factors such as ease of tape use, can be used to inform the choice of tape type for this application.

4.4. The effect of tape storage temperature

To explore the effect of tape storage temperature on the reflected log efficiency measure of fibre retrieval efficacy, a set of simple effects

Table 5
Significant and discussable simple effects that explore the impact of tape type.

Tapes		Condition			Difference between mean reflected log efficiencies	Best tape	Degrees of freedom	F	Adjusted p	r	Significant at > 95% confidence	Effect size magnitude
Tape 1	Tape 2	Temp/$^{\circ}C$	Method	Surface								
Crystal Tabs	J-LAR	19	Zonal	Glossed MDF	−1.637	Crystal Tabs	1	50.141	3.013E-10	0.283	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	Plywood	−1.516	Crystal Tabs	1	43.022	8.684E-09	0.264	Yes	small-medium
Crystal Tabs	J-LAR	19	1 to 1	Brick	−1.500	Crystal Tabs	1	42.124	1.331E-08	0.261	Yes	small-medium
Crystal Tabs	J-LAR	-5	Zonal	Brick	−1.458	Crystal Tabs	1	39.793	4.054E-08	0.254	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	Ceramic tile	−1.399	Crystal Tabs	1	36.605	1.876E-07	0.244	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	Tracksuit trousers	−1.329	Crystal Tabs	1	33.051	1.049E-06	0.233	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	Cushion cover	−1.237	Crystal Tabs	1	28.654	9.012E-06	0.218	Yes	small-medium
Crystal Tabs	J-LAR	35	Zonal	Short carpet	−1.205	Crystal Tabs	1	27.181	1.862E-05	0.212	Yes	small-medium
Crystal Tabs	J-LAR	-5	Zonal	Short carpet	−1.189	Crystal Tabs	1	26.474	2.641E-05	0.210	Yes	small-medium
Crystal Tabs	J-LAR	19	1 to 1	Seatbelt	−1.146	Crystal Tabs	1	24.579	6.763E-05	0.202	Yes	small-medium
Crystal Tabs	J-LAR	-5	1 to 1	Brick	−1.053	Crystal Tabs	1	20.762	4.574E-04	0.187	Yes	small-medium
Crystal Tabs	J-LAR	19	1 to 1	Glossed MDF	−1.002	Crystal Tabs	1	18.778	1.248E-03	0.178	Yes	small-medium
Crystal Tabs	J-LAR	-5	1 to 1	Jeans	−0.993	Crystal Tabs	1	18.457	1.469E-03	0.176	Yes	small-medium
Crystal Tabs	J-LAR	19	1 to 1	Tracksuit trousers	−0.972	Crystal Tabs	1	17.700	2.160E-03	0.173	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	T-shirt	−0.954	Crystal Tabs	1	17.030	3.040E-03	0.169	Yes	small-medium
Crystal Tabs	J-LAR	19	Zonal	Jeans	−0.937	Crystal Tabs	1	16.420	4.156E-03	0.166	Yes	small-medium
Crystal Tabs	J-LAR	19	1 to 1	Cushion cover	−0.840	Crystal Tabs	1	13.206	2.189E-02	0.150	Discussable	small-medium
Residuals	NA	NA	NA	NA	NA	NA	576	NA	NA	NA	NA	NA

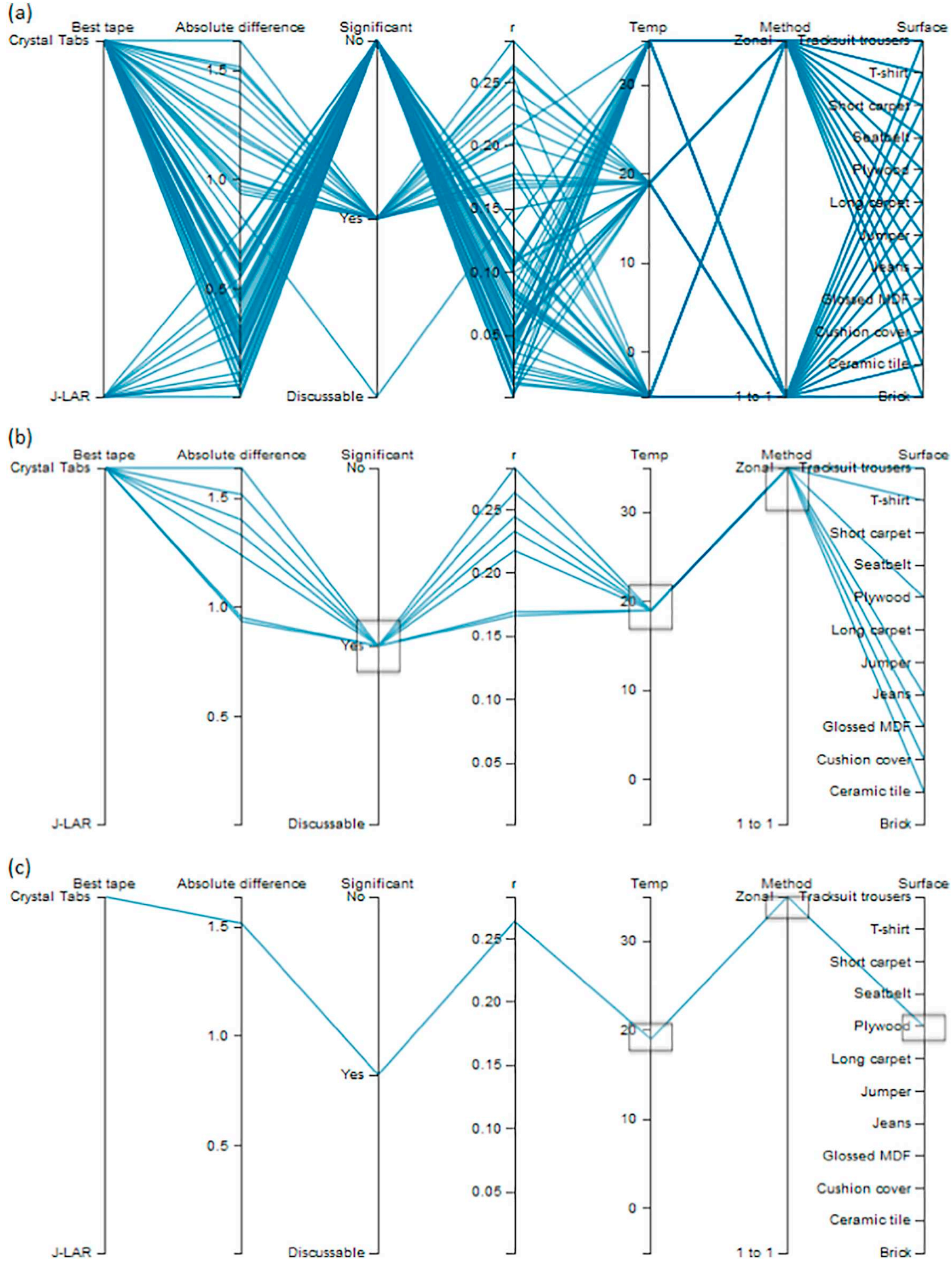

Fig. 11. Screen shots of an interactive parallel coordinate plot (available from [37]) that summarises the key findings of a simple effects analysis of the effects of tape type at fixed levels of tape storage temperature (Temp, in °C), taping method (Method) and Surface, using the Bonferroni adjustment to control the familywise error rate. Part (a) shows the full data set, and parts (b) and (c) illustrate the application of user-defined filters.

tests was carried out. This set consisted of one such test for each of the 48 unique combinations (i.e. conditions) of tape type, taping method and surface. In these tests, Bonferroni adjustment was employed to control the inflation in the familywise error rate.

As shown in Table 6, this process revealed that 12 of the tests (25% of the total) identified a significant simple effect and one test identified a discussible one. That Table also shows the effect size of these as measured by r. Further, it provides a categorisation of the magnitudes of these measurements based on the convention that values of r that are 0.10, 0.30 and 0.50 are small, medium and large, respectively [40, pp 79–81]. On this basis, each of the significant and discussable simple effects have effect sizes in the small to medium range. Interestingly, both tape types, both taping methods and all surfaces bar two (ceramic tile and long carpet) are amongst the conditions shown in Table 6. A

Table 6
Key output and effect size information from simple effects tests that were conducted to explore the effect of tape storage temperature on reflected log efficiency. Only those data from those tests that revealed significant or discussible simple effects are shown.

Condition			Degrees of freedom	F	Adjusted p	r	Significant at > 95% confidence	Effect size magnitude
Tape	Method	Surface						
J-LAR	Zonal	T-shirt	2	29.664	2.628E-11	0.221	Yes	small-medium
J-LAR	Zonal	Plywood	2	25.255	1.471E-09	0.205	Yes	small-medium
Crystal Tabs	1 to 1	Seatbelt	2	22.825	1.386E-08	0.195	Yes	small-medium
J-LAR	Zonal	Jeans	2	21.052	7.199E-08	0.188	Yes	small-medium
Crystal Tabs	1 to 1	Jeans	2	19.183	4.129E-07	0.180	Yes	small-medium
J-LAR	Zonal	Glossed MDF	2	18.750	6.200E-07	0.178	Yes	small-medium
J-LAR	Zonal	Tracksuit trousers	2	13.250	1.136E-04	0.150	Yes	small-medium
J-LAR	1 to 1	Tracksuit trousers	2	12.151	3.255E-04	0.144	Yes	small-medium
Crystal Tabs	Zonal	Jeans	2	10.935	1.048E-03	0.136	Yes	small-medium
J-LAR	Zonal	Cushion cover	2	10.207	2.115E-03	0.132	Yes	small-medium
J-LAR	Zonal	Jumper	2	9.425	4.505E-03	0.127	Yes	small-medium
Crystal Tabs	1 to 1	Brick	2	8.497	1.107E-02	0.121	Yes	small-medium
Crystal Tabs	Zonal	Short carpet	2	7.222	3.831E-02	0.111	Discussable	small-medium
Residuals	NA	NA	576	NA	NA	NA	NA	NA

table of the data presented in Table 6 but for all 48 simple effects tests can be found in this paper's Supplementary materials and the R script written to create it is available elsewhere [27].

For the significant and discussible simple effects, pairwise contrasts were carried out to determine the identity of significant differences in mean reflected log efficiencies between the tape storage temperatures used in this study. In these contrasts, to control the familywise error rate, Tukey HSD adjustment was applied to each p value. This adjustment was based on the total number of means involved in the experiment as a whole (i.e. 144) and the residuals' degrees of freedom (i.e. 576). Table 7 shows synoptic data for those of the above-described contrasts that are statistically significant. None of the three contrasts for which the corresponding simple effect was discussable proved to be significant. A table showing the synoptic data given in Table 7 but for all the pairwise contrasts is available in this paper's Supplementary Materials and the R script written to create it is available online [27].

Of the contrasts shown in Table 7, all concern those between 19°C and either -5 or 35°C. This is in keeping with the relative similarities of the box plots for the temperature extremes (Fig. 4) and the apparent dissimilarity of those plots with the box plot for 19 °C. Interestingly a comparison of the median values shown in Fig. 4 shows that, overall, the efficiency of fibre retrieval is typically greater for both −5 and 35 °C than it is for 19 °C. Perhaps unsurprisingly, this typical behaviour is also echoed in Table 7. This shows that of the 14 significant pairwise contrasts, all of which involve 19 °C, there are only 2 for which this tape storage temperature resulted in the better fibre recovery rate (i.e. the lower of the two reflected log efficiencies under consideration). These observations need to be viewed in the wider context, however. In this study as a whole, there is a total of 144 possible pairwise comparisons (48 conditions × 3 temperature-based pairwise comparisons), so those 14 that are significant are 9.7% of the total, making them relatively rare. This too is in keeping with the box plots of Fig. 4, which show a good degree of overlap in the efficiency data between the three storage temperatures of the study.

To avoid the unnecessary exposure of the tapes to different temperatures, a different roll of each of J-LAR and Crystal Tabs was used for each of the three storage temperatures studied. Therefore, one hypothetical explanation of the effects described in the previous paragraph is that they are due to differences in the performance of different rolls of the same tape type. Given the automated nature of tape manufacture, this seems to be an unlikely explanation but remains one of interest for future work.

An interactive parallel coordinate plot has been created and made available online to show the pairwise between-temperature differences in reflected log efficiency for each of the unique combinations of tape type, taping method and surface [37]. Screen shots of this plot in use have been reproduced in Fig. 12. The three parts of that figure compare the performance of tape stored at −5 and 19 °C [part (a)], −5 and 35 °C [part (b)] and 19 and 35 °C [part (c)]. In each of these parts of that Figure, the user has applied filters to the data. In each case, these show which of the two storage temperatures under consideration were found to produce the better (i.e. lower) mean reflected log efficiency figure when Crystal Tabs tape was used with the zonal taping method on jeans. Fig. 12(a) shows that, under these conditions, tape stored at −5 °C outperformed that stored at 19 °C with an absolute difference between the mean reflected log efficiencies of between 0.50 and 0.75 and an effect size as measured by r of between 0.100 and 0.125 but that this difference was not statistically significant. From Fig. 12(b), it can be seen that, under the same conditions, tape stored at 35 °C outperformed that stored at −5 °C, with an absolute difference in mean reflected log efficiency of between 0.4 and 0.6 and an effect size (r) of less than 0.1 but that this too is not a statistically significant difference. In contrast, Fig. 12(c) shows that, under the same conditions, there is a significant difference in performance (as measured by mean reflected log efficiency) between tape stored at 19 °C with that stored at 35 °C, with the latter outperforming the former with an absolute difference of > 1.0 and an effect size (r) of between 0.175 and 0.2. By use of this plot, the user can explore any given combination of tape type, taping method and surface that was employed in this study to establish which of the tape storage temperatures used resulted in the best fibre retrieval efficiency. It also shows the user whether the pairwise differences seen are significant and their effect sizes.

Qualitative observations were also made during this study on the effect of tape storage temperature on each tape type's ease of use. It was noted that J-LAR was more prone to rip during use when it was stored at −5 °C than when stored at either of the other temperatures of the study. This problem could be avoided in the field by allowing the tape to warm prior to use. No such effect of temperature on the propensity to tear was seen for Crystal Tabs. However, it was observed that this tape became more pliant with increasing storage temperature. The implication of this is that it is easier to apply this tape to convoluted surfaces when it is stored under warm conditions.

4.5. *The effect of taping method*

A simple effects analysis was completed to explore the effect of taping method (one-to-one or zonal) on mean reflected log efficiency. During this, one simple effect test was carried out for each of the 72 unique combinations (i.e. conditions) of tape storage temperature, tape type and surface. The familywise error rate was controlled by using the Bonferroni adjustment. This showed that, during the experiment, in 53 of the 72 conditions tested (i.e. 73.6%), one-to-one taping captured a

Table 7
Pairwise contrasts that show statistically significant differences in mean reflected log efficiencies between tapes stored at different temperatures.

Temperatures/°C		Condition			Simple effect significant at > 95% confidence	Difference between mean reflected log efficiencies	Better temperature/°C	Degrees of freedom	F	Adjusted p	Pairwise contrast significant at > 95% confidence	r	Effect size magnitude
Temp. 1	Temp. 2	Tape	Method	Surface									
19	35	J-LAR	Zonal	Cushion cover	Yes	1.041	35	1	20.297	4.700E-02	Yes	0.184	small-medium
19	35	J-LAR	Zonal	Glossed MDF	Yes	1.412	35	1	37.323	1.802E-05	Yes	0.247	small-medium
-5	19	Crystal Tabs	1 to 1	Jeans	Yes	−1.306	−5	1	31.908	2.345E-04	Yes	0.229	small-medium
19	35	Crystal Tabs	1 to 1	Jeans	Yes	1.162	35	1	25.252	5.248E-03	Yes	0.205	small-medium
19	35	Crystal Tabs	Zonal	Jeans	Yes	1.080	35	1	21.816	2.449E-02	Yes	0.191	small-medium
-5	19	J-LAR	Zonal	Jeans	Yes	−1.107	−5	1	22.933	1.496E-02	Yes	0.196	small-medium
19	35	J-LAR	Zonal	Jeans	Yes	1.430	35	1	38.270	1.150E-05	Yes	0.250	small-medium
-5	19	J-LAR	Zonal	Plywood	Yes	−1.386	−5	1	35.968	3.427E-05	Yes	0.242	small-medium
19	35	J-LAR	Zonal	Plywood	Yes	1.457	35	1	39.706	5.822E-06	Yes	0.254	small-medium
-5	19	Crystal Tabs	1 to 1	Seatbelt	Yes	1.430	19	1	38.266	1.152E-05	Yes	0.250	small-medium
19	35	Crystal Tabs	1 to 1	Seatbelt	Yes	−1.259	19	1	29.661	6.765E-04	Yes	0.221	small-medium
-5	19	J-LAR	Zonal	T-shirt	Yes	−1.590	−5	1	47.336	1.594E-07	Yes	0.276	small-medium
19	35	J-LAR	Zonal	T-shirt	Yes	1.488	35	1	41.460	2.538E-06	Yes	0.259	small-medium
19	35	J-LAR	Zonal	Tracksuit trousers	Yes	1.129	35	1	23.854	9.903E-03	Yes	0.199	small-medium
Residuals	NA	NA	NA	NA	NA	NA	NA	576	NA	NA	NA	NA	NA

larger proportion of the target fibres than did the zonal taping method (as expressed by the mean reflected log efficiency measure); whereas for 19 conditions (26.4% of the total), the reverse was true. This echoes the effect seen in Fig. 5 which shows that, overall, one-to-one taping typically outperformed zonal taping but with a substantial degree of overlap in performance.

Table 8 summarises the outcomes of that analysis of taping method for those conditions for which statistically significant or discussable effects were found at a confidence level of > 95%. In each case, the figure in the column labelled 'Difference …' was calculated by subtracting the mean reflected log efficiency figure for one-to-one taping from that of zonal taping for the condition shown in columns 3, 4 and 5. Therefore, the fact that all the figures in the 'Difference …' column are negative shows that none of the 19 conditions for which zonal taping outperformed one-to-one taping are statistically significant and that, for the conditions for which the reverse is true, 10 (i.e. those listed in the table, 13.9% of the total) produced statistically significant or discussable results. As can be seen from Table 8, the effect size for each of these significant or discussable differences has been measured using r. Adopting the convention that r values of 0.10, 0.30 and 0.50 represent small, medium and large effect sizes, respectively [40, pp. 79–81], means that all the effects shown in Table 8 are in the small to medium range. The complete version of Table 8 is provided in this paper's Supplementary materials and the R script written to generate it is available elsewhere [27].

The initial impression given by Table 8 is that the distribution of surface types present is much as might be expected by chance. However, it is perhaps interesting to note that although all three storage temperatures and both tape types are present in the conditions shown in Table 8, both room temperature (19 °C) and J-LAR are over represented. These levels of the factors Temp and Tape appear seven times each. If they were present in *pro-rata* numbers, they would be expected to occur in 3.3 and five times, respectively. To explore this further, three exact goodness of fit tests were carried out, one for each of the three factors (Tape, Temp and Surface) that make up the conditions shown in Table 8. This was done to determine whether the pattern of distribution of the levels of these factors seen in that table is significantly different from that expected if they had been present on a *pro rata* basis. The unadjusted p values from these tests were found to be 0.3438, 0.0931 and 0.6964 for Tape, Temp and Surface, respectively – none of which exhibit statistical significance at a 95% level of confidence. This suggests that, despite initial impressions to the contrary, a distribution pattern that could result in the over-representation of 19 °C and J-LAR amongst the conditions seen in Table 8 is within what might be expected based on chance alone.

Fig. 13 provides screenshots from a parallel coordinate plot that summarises the result of the simple effects analysis of the effect of taping method for all 76 conditions. The plot itself is available online [37]. Part (a) of that Figure shows the full data, whereas part (b) provides an example of the plot in use. In the latter, the user has applied filters to identify those surfaces for which there is a significant difference in the efficiency of the two taping methods when employing Crystal Tabs tape that has been stored at room temperature (19 °*C*). It also allows the user to see the range of absolute difference in performance between these taping methods (as expressed by reflected log efficiency) and the range of effect size (as measured by r) of these differences. Such information could be used to inform forensic strategy.

Unlike the one-to-one method, its zonal counterpart gives the potential for fibres collected from one area of the surface to be redistributed to another when the piece of tape used is re-applied, leaving the possibility that such redistributed fibres may not be recovered. As implied elsewhere [6], the one-to-one method also provides a more systematic approach to the recovery of fibres than does the zonal alternative. During one-to-one taping, the entire area to be sampled is covered with tapes before their removal, thereby ensuring the entire target area is contacted with tape. In contrast, during zonal taping, the same piece of tape is

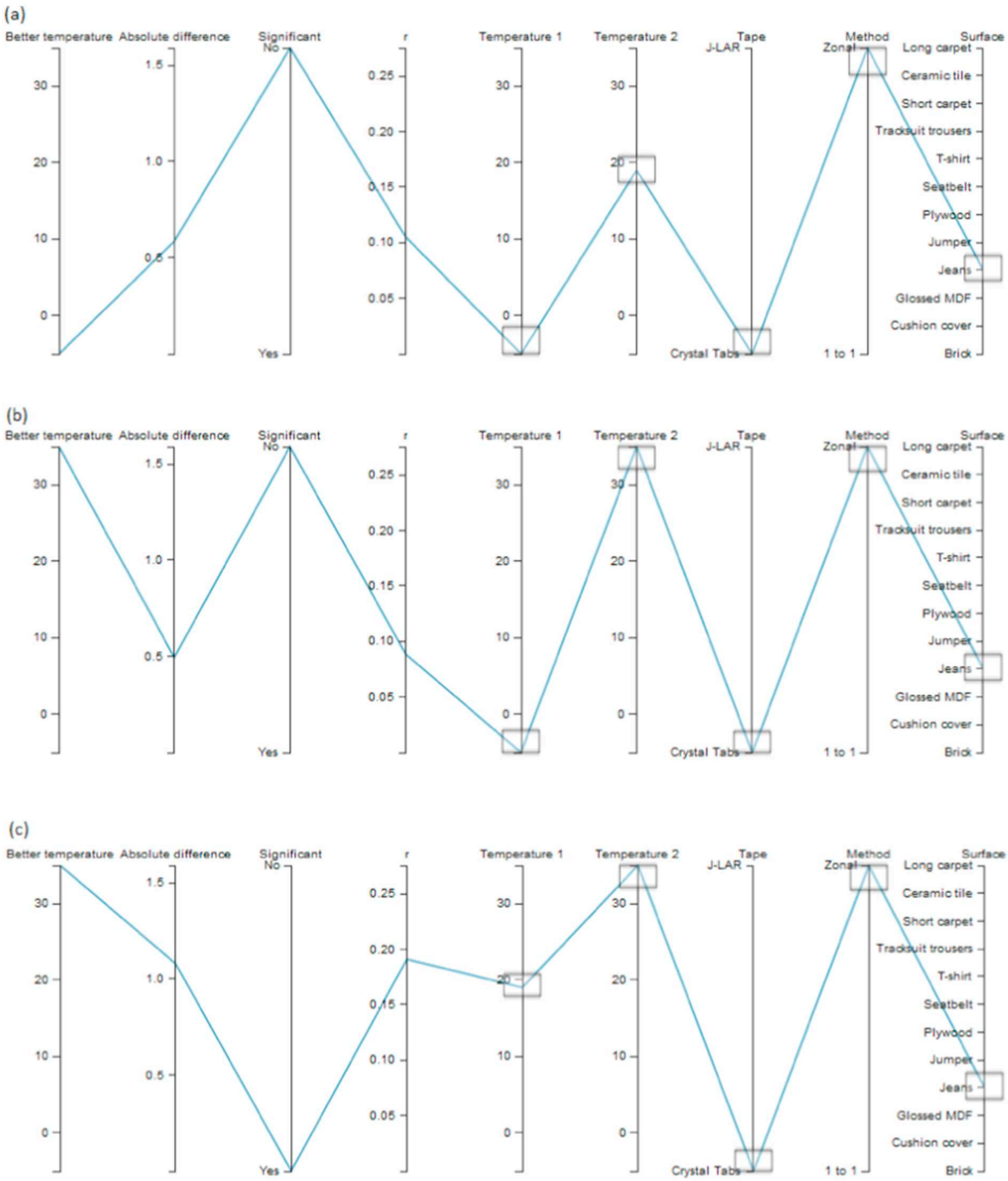

Fig. 12. Screen shots of an interactive parallel coordinate plot (available from [37]) showing pairwise between-temperature differences in reflected log efficiency for each of the unique combinations of tape type (Tape), taping method (Method) and Surface. Note that °C are the units of temperature used here. Parts (a), (b) and (c) illustrate the application of user-defined filters – see the main text for details.

repeatedly applied to and removed from the targeted area. This leaves the possibility that some of that area may be missed as there is no visible indication of where has and where has not been previously in contact with the tape. Further, the fibres and other debris collected during one application of the tape in the zonal method may place a physical barrier between the tape's adhesive and any given target fibre on the surface during a subsequent application of the tape, thus impeding the recovery of that fibre. Taken together, these observations may explain why, as outlined above, whilst not universally the case, the one-to-one method typically recovered a greater proportion of the target fibres present than did the zonal taping method.

During this study, as described in Section 2.2, care was taken to use the same procedure each time a piece of tape was applied to a surface. However, inevitably, the pressure used when doing this will have varied between such applications. Whilst the impact of this variation is not known, it seems likely that it will account for some of the unexplained variance present in the fibre retrieval rate data.

Whilst not within the remit of this study, it was noted that, when processing highly sheddable surfaces, the zonal method produced tape lifts which contained more background material than did the one-to-

Table 8
Significant and discussable simple effects that explore the impact of taping method.

Methods		Condition			Difference between mean reflected log efficiencies	Best method	Degrees of freedom	F	Adjusted p	r	Significant at > 95% confidence	Effect size magnitude
Method 1	Method 2	Tape	Temp/°C	Surface								
1 to 1	Zonal	Crystal Tabs	19	Seatbelt	−1.667	1 to 1	1	51.989	1.269E-10	0.288	Yes	small-medium
1 to 1	Zonal	J-LAR	19	Plywood	−1.428	1 to 1	1	38.146	8.936E-08	0.249	Yes	small-medium
1 to 1	Zonal	Crystal Tabs	19	Brick	−1.312	1 to 1	1	32.206	1.583E-06	0.230	Yes	small-medium
1 to 1	Zonal	J-LAR	19	Jeans	−1.283	1 to 1	1	30.789	3.162E-06	0.225	Yes	small-medium
1 to 1	Zonal	J-LAR	19	T-shirt	−1.246	1 to 1	1	29.036	7.466E-06	0.219	Yes	small-medium
1 to 1	Zonal	J-LAR	19	Ceramic tile	−1.089	1 to 1	1	22.204	2.216E-04	0.193	Yes	small-medium
1 to 1	Zonal	J-LAR	-5	Jumper	−1.062	1 to 1	1	21.103	3.853E-04	0.188	Yes	small-medium
1 to 1	Zonal	Crystal Tabs	35	T-shirt	−0.932	1 to 1	1	16.259	4.514E-03	0.166	Yes	small-medium
1 to 1	Zonal	J-LAR	19	Seatbelt	−0.867	1 to 1	1	14.069	1.397E-02	0.154	Discussable	small-medium
1 to 1	Zonal	J-LAR	35	Ceramic tile	−0.819	1 to 1	1	12.560	3.068E-02	0.146	Discussable	small-medium
Residuals	NA	NA	NA	NA	NA	NA	576	NA	NA	NA	NA	NA

one method. The presence of such material could have a negative effect on the ease of subsequent analysis [5,9]. Therefore, from this perspective, when approaching a highly sheddable surface, the one-to-one method may be deemed preferable to the zonal one. However, the size of the area that requires tape lifting would also need to be considered as the one-to-one method produces more tape lifts per unit area than does zonal taping, which may mean that the former is not time- or cost-effective [6,35]. From these observations, it is clear that the efficiency of target fibre retrieval is not the only matter that should be considered when deciding which taping method to use in any given case.

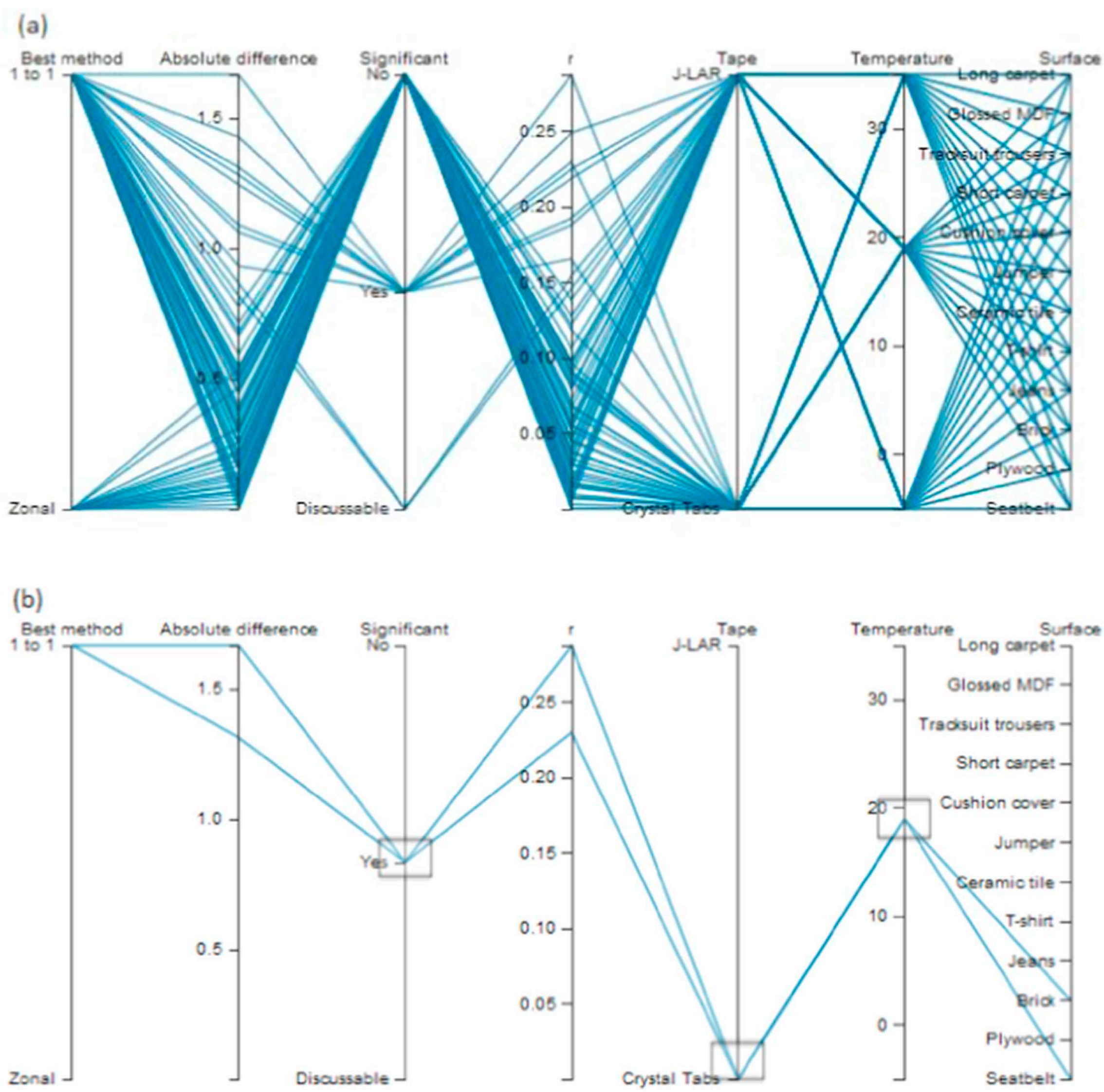

Fig. 13. Screen shots of an interactive parallel coordinate plot (available from [37]) that summarises the key findings of a simple effects analysis of the effect of taping method at fixed levels of tape storage temperature (Temp, in °C), tape type (Tape) and Surface, using the Bonferroni adjustment to control the familywise error rate. Part (a) shows the full data set and part (b) illustrates the application of user-defined filters.

Table 9
Simple effects that explore the impact of surface.

Condition			Degrees of freedom	F	Adjusted p	r	Significant at > 95% confidence	Effect size magnitude
Temp/°C	Tape	Method						
19	Crystal Tabs	1 to 1	11	49.180	1.59E-74	0.280	Yes	small-medium
19	Crystal Tabs	Zonal	11	38.102	2.40E-60	0.249	Yes	small-medium
35	Crystal Tabs	1 to 1	11	36.178	1.02E-57	0.243	Yes	small-medium
−5	Crystal Tabs	Zonal	11	34.907	5.98E-56	0.239	Yes	small-medium
35	Crystal Tabs	Zonal	11	32.790	5.95E-53	0.232	Yes	small-medium
35	J-LAR	1 to 1	11	32.669	8.87E-53	0.232	Yes	small-medium
-5	J-LAR	Zonal	11	31.212	1.13E-50	0.227	Yes	small-medium
-5	Crystal Tabs	1 to 1	11	31.148	1.40E-50	0.227	Yes	small-medium
35	J-LAR	Zonal	11	28.889	3.05E-47	0.219	Yes	small-medium
19	J-LAR	1 to 1	11	28.825	3.81E-47	0.218	Yes	small-medium
-5	J-LAR	1 to 1	11	26.255	3.06E-43	0.209	Yes	small-medium
19	J-LAR	Zonal	11	21.473	1.17E-35	0.190	Yes	small-medium
Residuals	NA	NA	576	NA	NA	NA	NA	NA

4.6. The effect of surface type

As shown in Table 4, the main effect of Surface is both significant and substantive. Figs. 6 to 8 allow some of the details of that effect to be seen. In Section 4.1, there is a reflection on the effect of Surface, as seen in this study, in the light of relevant previously reported work.

Importantly, as seen in Table 4, the Tape:Temp:Method:Surface interaction is also significant. The interplay between the effect of Surface and each of the other factors in this term has been analysed by a two-stage process.

Firstly, simple effects tests, one for each unique combination (i.e. condition) of Tape, Temp and Method, were carried out with Bonferroni adjustment to both p and alpha as described in Section 2.3. As shown in Table 9, all 12 of these tests showed significant differences between mean reflected log efficiencies amongst the surfaces included in this study.

Secondly, to find where the significant differences were located amongst these surfaces, pairwise contrasts were carried out. As all the simple effects had proved to be significant, all 792 possible pairwise comparisons were tested in this way. In this process, Tukey HSD adjustments were made to the p values to control the family wise error rate based on 144 means and 576 degrees of freedom. A table showing the outcome of all 792 tests, in order of decreasing effect size as measured by r, is provided in this paper's Supplementary materials and the R script written to generate that table is available elsewhere [27]. The top and bottom 10 rows of that table are reproduced in Table 10. As shown in the full version of Table 10 (in the Supplementary materials), 367 (i.e. 46.3%) of the between Surface pairwise differences between mean reflected log efficiencies are significant at a confidence level of > 95%. Using the benchmark figures for r of 0.10 = small, 0.30 = medium and 0.50 = large as cut points [40, pp. 79–81], those significant differences are seen to have effect sizes either in the small-to-medium or medium-to-large size ranges.

Hierarchical cluster analysis based on efficiency median and interquartile range data for the 12 surfaces has revealed the presence of three highly stable clusters[3] [27], the membership of which is shown in Fig. 14. The high stability of these clusters suggests that they represent true structures in the data [41, p184]. These structures are echoed in the behaviour revealed in Table 10 and its complete counterpart (the latter is in this paper's Supplementary materials).

That table shows the number of the cluster to which each of the surfaces belong. It also contains a column containing Cluster Number Difference (CND) data. Noting that the better surface is that which has a lower mean reflected log efficiency value, the data in that column were calculated by subtracting, for each pairwise contrast, the cluster number of the worse surface from that of the better surface. Thus, the data in that column provides the following information:

- if CND < 0 then the better surface is from a cluster that has a lower median fibre retrieval rate and higher interquartile range of such rates;
- if CND = 0 then the better surface is from the same cluster as the worse surface;
- if CND > 0 then the better surface is from a cluster that has a higher median fibre retrieval rate and lower interquartile range of such rates;
- if the absolute value of the CND is 1, the two surfaces are from neighbouring clusters in Fig. 14;
- if the absolute value of the CND is 2, the two surfaces are from clusters 1 and 3 (i.e. those with the maximum differences in median and interquartile range).

As would be expected, there is a strong correlation (0.800) between r and CND in the data to be found in the complete version of Table 10 (provided in this paper's Supplementary materials). To explore this further, the tertiles of r were use as cut points to separate the values of r in that table into three categories, namely bottom, middle and top. The resulting categorical data was then cross tabulated with the complete CND data, creating the contingency table shown in Table 11. This shows a clear association between r category and CND, which Pearson's Chi-squared test of association proved to be highly significant ($\chi^2 = 619.35$, df = 6 and p < 2.2e-16).

As can be seen from Table 11, the modal value of the CND for the bottom-, middle- and top-thirds of the r values is 0, 1 and 2, respectively. This shows that, as exemplified in Table 10, those comparisons that appear near to the top of the complete version of that table are typically between surfaces taken pairwise from between clusters 1 and 3 where as those near the bottom are typically taken from within any one of the three clusters. Further, the central third of the rows of the complete version of that table are dominated by comparisons between surfaces found in clusters that are nearest neighbours in Fig. 14.

It seems probable that the observations made concerning Table 11 are simply reflections of the previously noted stability of the three clusters shown in Fig. 14.

An interactive parallel coordinate plot has been created to summarise and display the results of the between surface pairwise comparison analysis of the reflected log efficiency data. This is available online [37] and allows the user to filter the data to find points of

[3] The stability of the clusters was evaluated by means of the clusterboot() function in the fpc package [18] for R. This revealed stability values of 0.991, 1.000 and 0.980 for clusters 1, 2 and 3, respectively [27]. Zumel and Mount provide a rule of thumb for the interpretation of such values, according to which, values > Ca. 0.85 indicate high stability [41, p184].

Table 10
Surface pairwise contrasts (ordered by effect size as measured by r).

Position in full table	Surfaces				Condition			Simple effect significant at > 95% confidence	Difference between mean reflected log efficiencies	Better surface	Cluster Number Difference (CND)	Degrees of freedom	F	Adjusted p	Pairwise contrast significant at > 95% confidence	r	Effect size magnitude
	Surface 1		Surface 2		Temp/°C	Tape	Method										
	Surface	Cluster No.	Surface	Cluster No.													
Top 10 rows	Glossed MDF	3	Jeans	1	19	Crystal Tabs	1 to 1	Yes	−2.883	Glossed MDF	2	1	155.550	5.040E-10	Yes	0.461	medium-large
	Glossed MDF	3	Long carpet	1	35	Crystal Tabs	1 to 1	Yes	−2.844	Glossed MDF	2	1	151.350	5.040E-10	Yes	0.456	medium-large
	Glossed MDF	3	Jumper	1	35	Crystal Tabs	1 to 1	Yes	−2.836	Glossed MDF	2	1	150.506	5.040E-10	Yes	0.455	medium-large
	Glossed MDF	3	Long carpet	1	19	Crystal Tabs	Zonal	Yes	−2.832	Glossed MDF	2	1	150.126	5.040E-10	Yes	0.455	medium-large
	Glossed MDF	3	Jumper	1	35	Crystal Tabs	Zonal	Yes	−2.818	Glossed MDF	2	1	148.629	5.040E-10	Yes	0.453	medium-large
	Glossed MDF	3	Long carpet	1	35	Crystal Tabs	Zonal	Yes	−2.791	Glossed MDF	2	1	145.744	5.040E-10	Yes	0.449	medium-large
	Glossed MDF	3	Jeans	1	19	Crystal Tabs	Zonal	Yes	−2.787	Glossed MDF	2	1	145.377	5.040E-10	Yes	0.449	medium-large
	Ceramic tile	3	Jeans	1	19	Crystal Tabs	1 to 1	Yes	−2.781	Ceramic tile	2	1	144.792	5.040E-10	Yes	0.448	medium-large
	Glossed MDF	3	Short carpet	1	35	J-LAR	Zonal	Yes	−2.780	Glossed MDF	2	1	144.672	5.040E-10	Yes	0.448	medium-large
	Long carpet	1	Plywood	3	35	Crystal Tabs	1 to 1	Yes	2.733	Plywood	2	1	139.788	5.041E-10	Yes	0.442	medium-large
Bottom 10 rows	Long carpet	1	Tracksuit trousers	2	19	J-LAR	Zonal	Yes	−0.013	Long carpet	-1	1	0.003	1.000E+00	No	0.002	< small
	Jeans	1	T-shirt	2	-5	Crystal Tabs	Zonal	Yes	0.013	T-shirt	1	1	0.003	1.000E+00	No	0.002	< small
	Jeans	1	T-shirt	2	-5	Crystal Tabs	1 to 1	Yes	0.011	T-shirt	1	1	0.002	1.000E+00	No	0.002	< small
	Jeans	1	Long carpet	1	-5	Crystal Tabs	Zonal	Yes	−0.010	Jeans	0	1	0.002	1.000E+00	No	0.002	< small
	Cushion cover	1	Long carpet	1	35	J-LAR	1 to 1	Yes	0.010	Long carpet	0	1	0.002	1.000E+00	No	0.002	< small
	Brick	2	Seatbelt	2	35	J-LAR	1 to 1	Yes	−0.009	Brick	0	1	0.001	1.000E+00	No	0.002	< small
	Jumper	1	Long carpet	1	35	Crystal Tabs	1 to 1	Yes	−0.008	Jumper	0	1	0.001	1.000E+00	No	0.001	< small
	Glossed MDF	3	Plywood	3	-5	J-LAR	1 to 1	Yes	−0.008	Glossed MDF	0	1	0.001	1.000E+00	No	0.001	< small
	Cushion cover	1	Short carpet	1	-5	Crystal Tabs	1 to 1	Yes	−0.006	Cushion cover	0	1	0.001	1.000E+00	No	0.001	< small
	Ceramic tile	3	Plywood	3	-5	Crystal Tabs	1 to 1	Yes	0.001	Plywood	0	1	0.000	1.000E+00	No	0.000	< small
Residuals	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	576	NA	NA	NA	NA	NA

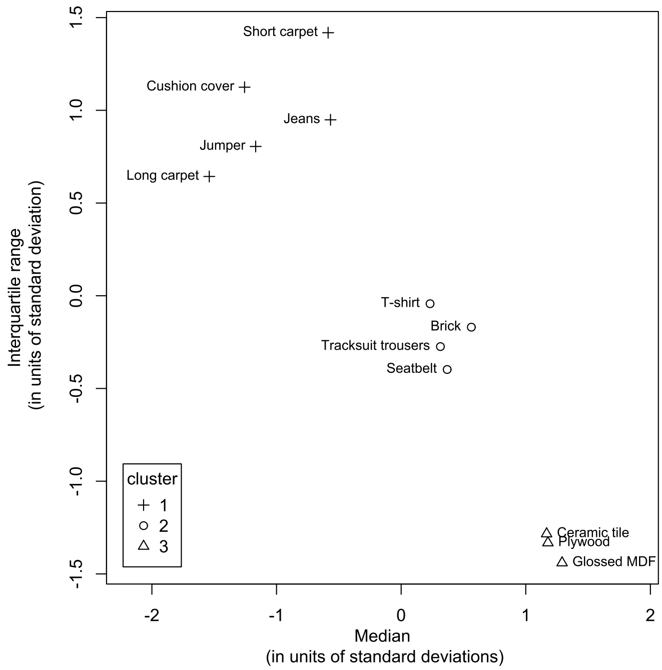

Fig. 14. Surface clusters based on the median and interquartile range of fibre retrieval rate data.

Table 11
A cross tabulation of classified r values and Cluster Number Difference data. In this, r values are classified according to whether they appear in the top, middle or bottom third of the complete version of Table 10.

r in which third?	Cluster number difference				
	−1	0	1	2	Sum
Bottom	17	173	74	0	264
Middle	1	54	200	9	264
Top	0	1	92	171	264
Sum	18	228	366	180	792

interest. A screen shot showing this plot in use is given in Fig. 15. In this instance, the user has applied filters to isolate the comparison between the mean reflected log efficiencies with which fibres were retrieved from short carpet and glossed MDF surfaces using Crystal Tabs stored at room temperature (19°C), employing the zonal method. It shows that under these conditions, the absolute difference between the mean reflected log efficiencies for these two surfaces was Ca. 2.5, that this difference is significant at a confidence level of > 95% and has an effect size as measured by r of Ca. 4.1.

The information that is presented in Tables 10 and 11, and Figs. 14 and 15, and their online counterparts, is important as it may act as a springboard to the study of the fundamental mechanisms that underpin target fibre transfer and persistence. However, it has limited direct applicability at the crime scene. This is because the choice of surfaces from which to collect fibres evidence is not under the control of the crime scene investigator as it is dictated by those surfaces which are present at the scene. Furthermore, which of those surfaces are to be sampled for fibres evidence will depend on an assessment of the impact of such sampling on other trace evidence (such as fingermarks) which may also be present. Also, the number of target fibres that may be retrieved from any given surface is not only dependent on the efficiency of the retrieval process. It also depends on how many of these fibres are present on that surface. This is controlled by the nature and degree of contact between the surface and the target fibre donor, and the subsequent loss of target fibres from that surface before crime scene processing has occurred (indeed, in a recent paper, the flying of drones above surfaces on which yarn had been placed was shown to result in the displacement of that yarn [42]). As shown in Fig. 14, in this study, fibre retrieval efficiencies were greater from smooth non-textile surfaces than from textile ones. However, it is possible that the latter are better at capturing fibres from garments worn by those involved in the crime than are the former; this is not something that was studied in the work reported here.

Notwithstanding the caveats of the previous paragraph, there are circumstances in which the data from this study can usefully inform crime scene decision making. If a choice is to be made between two surfaces, one smooth and the other a rough textile material, and if that choice is to be based solely on the efficiency of fibre recovery, the data from this study suggest that the smooth non-textile one would be the better choice. Furthermore, the full version of Table 10 (given in this paper's Supplementary Materials) and the online counterpart of Fig. 15 [37] offer tools that have value in this regard. For any given combination of the tape types, tape storage temperatures and taping methods used in this study, they allow the user to find which of any two surfaces in this study yielded the higher rate of fibre recovery as determined by the mean reflected log efficiency statistic. These tools also allow the user to readily see the effect size associated with any such comparison and whether the observed difference in performance is statistically significant.

As described in Section 2.2, three techniques were used to apply the target fibres to the surfaces used in this study. For the jumper, carpets, cushion cover, jeans, T-shirt and tracksuit trousers (Surface Group A), the rubbing technique was used. If in any one instance, this deposited too few fibres, it was followed by the scraping technique until a total of

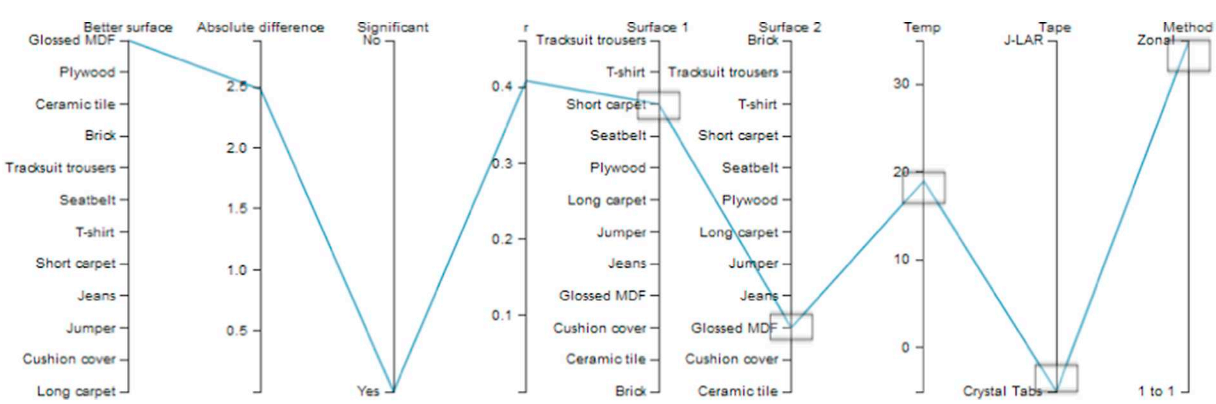

Fig. 15. Screen shot of an interactive parallel coordinate plot (available from [37]) showing pairwise between-surface differences in reflected log efficiency for each of the unique combinations of tape storage temperature (Temp, in °C), tape type (Tape) and taping method (Method). This illustrates the application of user-defined filters to the plot– see the main text for details.

100 to 200 target fibres transferred to the surface in question. For the brick surface (Surface Group B), the touching technique was employed. If needs be, this too was augmented by scraping as required to achieve the deposition of 100 to 200 target fibres per repeat determination. For the remaining surfaces (Surface Group C) – namely: seat belt, plywood, glossed MDF and ceramic tile – only the scraping technique was used.

The rubbing technique was applied to members of Surface Group A to mimic the dynamic contact that can occur during a crime between items such as garments worn by those present or those garments and other objects. Amongst bricks, the brick used in this study (Surface Group B) had a relatively smooth surface. Preliminary experiments revealed that the movement between the donor fabric and the surface that is integral to the rubbing technique displaced fibres from this surface. This meant that the desired number of target fibres in the test area (100 to 200) was not reached. To mitigate this problem, the touching technique was used on the brick surface. In the case of members of Surface Group C, neither the rubbing nor the touching technique could be used. This is because preliminary experiments revealed that for each of these surfaces, any contact with the donor garment resulted in the displacement of target fibres from the surface such that the desired number could not be attained. Therefore, for these surfaces, the scraping technique alone was employed.

It seems reasonable to assert that the differences in fibre retrieval rates observed between surfaces within each Surface Group should not be attributed to the effect of the fibre application technique. However, the same cannot be said of such differences between surfaces from different Surface Groups. In these cases, it is clear that some, if not all, of the effect of surface on the fibre retrieval rates seen in this study may in fact be due to differences in the target fibre application technique used.

If fibre application technique were wholly responsible for the differences in fibre retrieval rates between Surface Groups A, B and C, it would be expected that these groups would exactly correspond to the clusters seen in Fig. 14. As this is not the case and as those clusters were found to be stable, this strongly suggests that for some if not all surfaces, the effect of surface has a greater impact on fibre retrieval than does the method of target fibre application as used in this study. If true, this suggestion would be fortunate as, at the time of the processing of a crime scene, it is not normally known how the fibres present came to be there. Consider a circumstance in which there is a choice of two surfaces from which to recover fibres evidence and that this choice is to be based solely on which surface is likely to yield the highest fibre retrieval rate. If the aforementioned suggestion is correct for the surfaces in question, it would be possible to make an evidence-based decision about which surface to recover fibres from even when the means by which the fibres came to be present is not known.

In Section 4.1, the contrast between the relatively high fibre-retrieval rates reported here and those observed in previous studies is highlighted. As discussed in that section, this contrast may be attributable to between-study differences in target fibre application techniques and the use to which the surface was put between target fibre application and recovery. These observations, coupled with the matter discussed in the previous paragraph serve to identify that further work is needed. This is required to better understand the links between the mechanisms of target fibre transfer to and persistence on different surfaces and the rates at which these fibres may be subsequently recovered by tape lifting. This work would include testing the veracity of the strong suggestion identified in the preceding paragraph.

4.7. Limitations of the study

As described in Section 2.2, sandpaper was used to abrade the surface of the donor fabric from which the target fibres were obtained. This was done to facilitate the transfer of these fibres to the surfaces under study. This abrasion will have damaged those fibres. In particular, it is likely to have shortened them via fibre breakage. This may have influenced the likelihood of their subsequent recovery during tape lifting as well as altering their transfer behaviour. In a series of papers, Pounds and Smalldon explored in some detail the transfer and persistence of fibres consequent on simulated contact experiments [43,44,45]. Readers interested in the effect of fibre fragmentation on such behaviour are referred to those papers.

The findings reported here are based on the retrieval of target fibres that were present on the surfaces under study in the density range 0.30 to 0.91 fibres cm^{-2}. The target fibre application methods used (Section 2.2) are designed to achieve such densities via methods that the authors believe simulate circumstances in which such densities could be achieved in a crime scene setting. It is possible, therefore, that the retrieval rates seen in this study may not pertain in circumstances in which this simulation is inaccurate or when the fibre densities are outside the range mentioned above. Notwithstanding this caveat, as discussed in Section 4.6, there is reason to believe that for some if not all surfaces, the effect of surface on fibre retrieval is greater than that of the method of target fibre application as employed in this study.

The procedure used to apply tape to surface during this study is detailed in Section 2.2. Care was taken to use this procedure in as reproducible manner as possible. However, the pressure used during this aspect of the experimental work is unknown and almost certainly varied, at least to some extent, between such applications. The impact of this pressure on the fibre recovery rates seen is unknown save to say that its variation may have been responsible for some of the unexplained variance seen in those rates. It is entirely possible that the pressure used when applying tape to surface is a variable that has an important impact on target fibre recovery rate. However, so far as the authors are aware, there is no published work in this area. Therefore, it is their opinion that further work on this would be merited.

The primary concern of the study reported here was a quantitative assessment of the impact of four factors (tape type, tape storage temperature, taping method and surface type) on the recovery of target fibres. Of necessity, the range and number of levels of these factors was limited to those detailed in Section 2.1. Also, there are issues that are outside the remit of this work that nonetheless could or would have a bearing on crime scene strategy and tactics concerning trace evidence recovery using lifting tape.

In this study, scrupulous care was taken to ensure that the tapes were not contaminated with target fibres prior to use. This study did not include a systematic assessment of levels of contaminants that may be present on either of the tape types under study.

A qualitative assessment was carried out on the loss of the adhesive properties of the tape with the repeated touches required during the zonal taping method. It is this assessment that informed the maximum number of contacts between each tape type and each surface as detailed in Table 2. However, this assessment was not quantitative in nature. Wael et al. [5] report a method that they used to quantify this loss of adhesive qualities for five commercially available tapes (which did not include J-LAR or Crystal Tabs).

The work reported here is not concerned with the effectiveness with which different surfaces capture target fibres from donor objects (garments etc.), nor was it concerned with the effect of changes in humidity on the efficacy of fibre recovery.

Although this study examined the impact of multiple tape storage temperatures on fibre retrieval rates, only one temperature was used for the environment in which the tapes were used. This was room temperature (19 $\pm$ 1 $^{\circ}$C).

This study did not contain a between-roll comparison of the abilities of tape to recover fibre evidence. Also, to avoid the exposure of tape to unnecessary fluctuations in storage temperature, this study used one roll of each tape type at each of the tape storage temperatures. It remains a possibility, therefore, that the effect of tape storage temperature observed in this study is, in part at least, explained by between-roll differences in fibre recovery efficiency.

Assessment of ease of use of the tapes under study was limited to a qualitative evaluation of the effect of storage temperature on the tapes' pliability and propensity to tear.

Arguably, value-for-money and the ease of laboratory processing of the tapes are important considerations when setting forensic strategy and tactics. However, they are beyond the scope of this study. Similarly, this work was not concerned with the efficacy of the tapes at retrieving evidence types other than fibres (DNA, fingermarks etc.). In the paper by Wael *et al.* that is referred to above [5], they reported their evaluation of five attributes that relate to the ease of tape dissection, fibre removal and fibre slide making for each of the tape types included in their study.

The work reported here has identified the effects of the factors under study on the retrieval of target fibres applied to specific surfaces using specified techniques. However, it did not seek to expand our knowledge of the mechanisms that underpin these effects beyond that which is in the public domain and this remains an area in which further work is needed.

5. Conclusion

This study formed part of the validation of fibre tape lifting for Warwickshire & West Mercia Police. Its principal aim was to evaluate the effect of tape type (J-LAR or Crystal Tabs) and three other factors on fibre retrieval rates (i.e. efficiencies) using this lifting technique. The three other factors were:

- the temperature at which the tape was stored immediately prior to use at room temperature (19 ± 1 °C). There were three levels of storage temperature, namely −5 °C, 19 ± 1 °C and 35 °C;
- taping method (with two levels, namely zonal and one-to-one);
- surface type (with 12 levels, each being a surface, such as tracksuit trousers or glossed MDF, that is commonly encountered at crime scenes).

Five repeat efficiency determinations were carried out at each of the 144 unique combinations of the levels of these factors.

This is the first reported study to evaluate the target fibre retrieval efficiency of Crystal Tabs and the first to make such evaluations for J-LAR for surfaces other than those of garments. It provides a systematic evaluation of the effect of key factors that influence the fibre recovery performance of these tape types. However, as discussed in Section 4.7, there are considerations outside the remit of this study, such as value for money, that may also influence crime scene fibre recovery practice.

This study found that, as shown in Figs. 3 to 9, *typically*:

- Crystal Tabs retrieved a higher proportion of the target fibres than did J-LAR. Although, as indicated in Section 3 and discussed in Section 4.1, both Crystal Tabs and J-LAR performed well under all conditions of this study;
- target fibre retrieval rates for tapes stored at −5 °C and 35 °C were greater than for those stored at room temperature (19 ± 1 °C) [note, for reasons detailed in Section 4.7, it is possible that the effect of tape storage temperature observed in this study is to some degree attributable to between-roll differences in fibre recovery rates];
- one-to-one taping retrieved a higher proportion of the target fibres than did zonal taping;
- ceramic tile, glossed MDF and plywood yielded higher fibre recovery rates than did brick or textiles. Moreover, hierarchical cluster analysis (Section 4.6 and Fig. 14) detected that the surfaces under study could be divided into three stable clusters. This clustering was based on the median and interquartile range of the fibre retrieval rate achieved from each surface. This suggests that the behaviour of target fibres on surfaces within each of these clusters has more in common than does the behaviour of these fibres between them.

However, as also shown in Figs. 3 to 9, there is noticeable spread and overlap within the data, which means that knowledge of typical performance is not sufficient to fully understand the patterns seen. Also, matters such as tape pliability and the propensity of tape to tear may be of importance when formulating forensic tactics. During this study it was noted that J-LAR (but not Crystal Tabs) was more prone to rip when stored at −5 °C than when stored at either room temperature or 35 °C. Also, over the temperature range studied, the pliability of Crystal Tabs increased with storage temperature, suggesting that its efficacy when used on convoluted surfaces would be greater when stored under warm conditions.

A balanced four-way factorial ANOVA model has been built (see Table 4) with the reflected log fibre recovery rate as the dependent variable and all four of the factors listed above as the independent variables. This showed that all the main effects (tape, temperature, method and surface) to be both substantive and statistically significant. Crucially, it also revealed a significant interaction between all four of the study's factors, meaning that there is a complex interplay between their effects. From this the authors' conclude that any generalised recommendation, such as Crystal Tabs should be used instead of J-Lar, would be an oversimplification. Furthermore, it means that the typical picture described above must be evaluated in terms of that interplay between factors. This evaluation was achieved via simple effects analyses for the effect of tape type and taping method, and by simple effects analyses followed by pairwise contrasts for the effect of each of tape storage temperature and surface. By these means all pairwise differences in reflected log fibre recovery rates seen between conditions in which one factor has been varied have been considered. This has allowed tables and parallel coordinate plots to be drawn by which the user can readily establish which of any given pair of levels of each of the factors resulted in the higher fibre retrieval rate (as measured by reflected log efficiency). Furthermore, in each such instance, these tables and plots allow the user to see the effect size of the difference in performance and whether this difference is statistically significant. Extracts from these tables and plots can be seen in Tables 5, 7, 8 and 10 and Figs. 11 to 13 and 15. Full versions of these tables are provided in this paper's Supplementary materials and interactive versions of the plots are available online [37]. As far as is known by the authors, this is the first use of interactive parallel coordinate plots to display the outcome of the evaluation of significant interaction effects in a forensic science setting.

This paper includes a comparison of the findings of this study with those reported previously (Section 4.1). In Section 4.6 it also contains an exploration of the possible impact on fibre retrieval rates of the techniques used to apply the target fibres to the surfaces used in this study. Based on this comparison and exploration, the need for further work to better understand the interplay between the mechanisms of fibre transfer, persistence and recovery has been identified (Section 4.6).

Understanding the efficacy of commonly used tapes under different conditions, particularly different taping methods and storage temperatures, is important. It allows the optimisation of the recovery of trace evidence at crime scenes and in the laboratory, and can thereby inform standard operating procedures (SOPs) and quality assurance systems. The study reported here provides such an understanding concerning the rate at which fibres evidence is recovered by two commonly used tape types from 12 surfaces that are frequently encountered at crime scenes. It also provides a qualitative assessment of the impact of tape storage temperature on the pliability of these tape types and their propensity to tear during use. In the study reported here, there are 1080 pairwise comparisons in which only one of the factors varies. It is possible from the analysis presented in this paper to see for any one of these comparisons which of the pair produced the higher fibre retrieval rate as measured by its reflected log transform, and whether this difference in performance is significant and its effect size. This provides experimental evidence that can be used to inform the choices that forensic practitioners need to make when deciding between different fibre recovery options. The authors hope that they have presented the analysed data in formats (most notably tables and parallel coordinate plots) that make this evidence accessible. Based on this data and as mentioned in the Introduction, the authors have created and are now refining two web apps, one for SOP developers and one for SOP users [14]. The purpose of these apps is to assist the forensic practitioner in making informed choices which optimise performance and are validation compliant when retrieving fibres evidence. Those readers interested in these apps are encouraged to contact the corresponding author.

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