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ABSTRACT

The goal of this study is to establish statistically significant classifications of blood spatter patterns resulting from the interactions between a weapon, suspect and victim. Specifically, a "medium velocity" spatter pattern is usually attributed to blunt force injury, while a "high velocity" pattern is typically attributed to a gunshot wound. The differentiation between these classifications, however, has been qualitative and controversial. There are neither supporting statistical data nor are there objective criteria as to what constitutes "consistency" or the associated error rate. In this study, high speed video (at >10,000 frames per second) was used to visualize simulated bloodshedding events. The impact velocity of various blunt instruments, including a bat, crowbar, and hammer, onto blood soaked sponges was varied systematically. Analogous experiments were also performed with different caliber bullets fired with systematically varied distances to the target surface. In each case, the spatter drop size distribution and morphology was digitized and quantified using a series of rigorous metrics, thereby developing a large statistical "library" of spatter patterns. Photographs of the patterns were then assessed by trained analysts in a double-blind fashion, with the goal of providing quantitative error rates and testing objective criteria for the classification of medium and high velocity bloodstain patterns. We obtained two key findings. First, we demonstrate that quantitative metrics involving the *spatially-dependent size distribution* of droplets within a spatter pattern could serve as an objective means of differentiating gunshot and blunt instrument spatter patterns. Second, our double blind investigation revealed that human assessments yielded low error rates for gunshot spatter patterns (0.2%), but very high error rates for blunt instrument spatter patterns (37%). Our findings strongly suggest that (i) great caution should be exercised when identifying a pattern as resulting from a gunshot or blunt instrument impact in the absence of secondary indicia, and (ii) that further effort should be put toward development and refinement of quantitative image analysis procedures based on droplet spatial distributions.

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EXECUTIVE SUMMARY

Introduction and Background

Bloodstain pattern analysis (BPA) is a key tool in forensic science, aiding in crime scene reconstructions and helping to establish other elements of criminal acts (1,2). Some aspects of BPA are well understood by the community and are discussed in detail in standard texts for BPA. For example, arguably the most well-known BPA technique involves determination of the angle of impact of a droplet onto a surface, and using triangulation for several droplets to determine the point of origin (1,3). This triangulation methodology has been investigated extensively (4-6), with studies that provide rigorous assessments of error rates for both angle of impact (7) and point of origin (8).

Other aspects of BPA, however, remain less well understood. One important but controversial aspect involves the characterization of "impact spatter" patterns. Specifically, a common request made of BPA experts is to assess whether a particular spatter pattern was generated as a result of a blunt instrument impact or a more energetic impact, e.g., a gunshot. Early studies in the 1960s, including the seminal work by H.L. MacDonell, made a distinction between what they defined as "medium velocity" and "high velocity" impact spatter. MacDonell's original classification of bloodstain patterns focused on the quantity of "small" droplets (1) . High velocity patterns had "an extremely high percentage of very fine specks of blood…essentially all under 1/8 inch diameter", whereas medium velocity patterns had ""…many small droplets of 1/8 inch in diameter or smaller." [*]

Despite the widespread use of these definitions for almost 4 decades, however, over the past decade the terminology has fallen out of favor. The differentiation between medium and high velocity was increasingly viewed as subjective, with great risk of contextual bias affecting the assessment. In their assessment of the state of blood pattern analysis, the National Research Council noted that "some experts extrapolate far beyond what can be supported" and that "…many bloodstain pattern analysis cases are prosecution driven or

[*] Unless otherwise specified, throughout this report we use the terms "drop" or "droplet" interchangeably to refer to the dried stains left behind on a surface after evaporation of the liquid.

defense driven, with targeted requests that can lead to context bias" (9). Consideration of the above definitions provides insight on the underlying source of controversy: note that the definitions for medium and high velocity are not mutually exclusive. In MacDonell's definitions, both medium and high velocity impacts are defined as having many small droplets under 1/8 inch. In practice the differentiation hinged on the analyst's subjective impression of how many sufficiently small drops are present within a pattern. It is worth emphasizing that the National Research Council stated in their 2009 report that, "In general, the opinions of bloodstain analysts are more subjective than scientific" (10).

In this study, our main goal was to develop a quantitative methodology for differentiating spatter patterns generated by gunshot or blunt instrument impacts. Toward that end, we created spatter patterns under controlled conditions with various caliber bullets and different blunt instruments. Impact velocities were measured precisely using high speed video. We took these spatter patterns and analyzed them in two entirely different ways. First, custom image analysis algorithms were developed to automatically and rapidly extract quantitative measurements of the size distribution and spatial distributions of individual droplets within a spatter pattern. In this manner we measured approximately half a million individual droplets in 72 unique spatter patterns. A key result is that the mean size of droplets generated by gunshot is at most 30% smaller than in blunt instrument spatter, but that $f_{0.75}$, a spatially-dependent metric for fraction of droplets greater than 0.75 mm in diameter, is 600% greater for blunt instrument spatter. This finding suggests that quantitative metrics based on the spatially-dependent size distribution of droplets within a spatter pattern can provide a more robust and objective means for differentiating spatter patterns generated by gunshot or blunt instrument impact.

The second part of the analysis focused on identifying what conditions a bloodstain pattern analyst can accurately assess whether a particular blood spatter pattern was generated by a blunt instrument impact or a gunshot. Accordingly, we conducted a double-blind study of two cohorts – 10 highly experienced bloodstain pattern analysts and

10 inexperienced graduate students – who were asked to assess the same set of bloodstain patterns. The participants were provided no information other than the image of the pattern itself, thus preventing context bias. The key finding is that spatter patterns generated by gunshot were identified with high accuracy (0.2% error rate), but patterns generated by blunt instruments were correctly identified at much lower rates (38% error rate). Moreover, we demonstrate that analysts are statistically more likely to misidentify blunt instrument spatter patterns generated at small impact-to-target-surface distances because such impacts generate a higher fraction of smaller droplets. Our findings provide insight on situations where bloodstain analysts can confidently assess impact velocity, and should serve as a citable resource available to forensic scientists in states that have adopted the Daubert standard.

Research Methodology: Spatter Generation

All spatter patterns examined here were generated under controlled conditions in an underground firing range at the Sacramento County Laboratory of Forensic Sciences. Porcine (pig) blood with sodium citrate anticoagulant was used to generate the spatter patterns; immediately before each experiment, the blood was heated to human body temperature (37°C). To generate the impact spatter patterns, a sponge was soaked in blood until it adsorbed precisely 48 g blood. The sponge was then immediately placed on a wooden pedestal to be either hit with a blunt weapon (swung by hand) or shot with a firearm. White plotter paper acted as the vertical target surface and was placed at a specified distance L from the impact site. For the firearm experiments, the target paper was placed behind the sponge to catch the spatter; the bullet necessarily also passed through the paper, leaving a bullet hole. In contrast, for the blunt weapon experiments, the target paper was typically placed to the left of the sponge, since most of the spatter travelled in a direction orthogonal to the weapon impact. In all cases the sponge was loosely tied with a piece of string to the wooden platform to prevent the sponge from flying into the paper target following the impact. For each specified sponge-target distance, we conducted at least three replicates using three different caliber firearms (.357, 9 mm, .45) and three blunt instrument types (bat, hammer, crowbar) (Table 1). Note that one of the weapons, the baseball bat, was swung either at "half-strength" or "full-strength" by an adult male volunteer, with the qualitative magnitude of the strength characterized by the volunteer. All of the blunt instrument and gunshot impacts were recorded with high speed video (using a Phantom v7 camera) at approximately 10,000 to 15,000 images per second. Precise values of the impact velocity were then extracted from the high speed video.

Research Methodology: Quantitative Image Analysis

After allowing them to dry, each spatter pattern was photographed at high resolution to visualize as many of the small drops as possible. The patterns were photographed in approximately 1 square foot sections, using a 18.0 megapixel Canon digital camera and an macro lens. The patterns were illuminated for photography using four large flood lights which were positioned to provide uniform illumination. In this manner each spatter pattern generated between 16 and 25 individual images. The images were subsequently "stitched" together as seamlessly as possible in Photoshop to create one large image of the entire pattern. With our sensor and macro lens, each pixel in an image was 0.06 mm wide, and theoretically a droplet as small as 0.06 mm in diameter could be resolved. To be conservative, therefore, we operated under the assumption that all distances could be measured only to within ± 2 pixels, so that droplets had to be comprised of more than 4 pixels to be counted. For our setup this minimum number of pixels corresponds to a drop with diameter of 0.27 mm, which was thus chosen as the practical limit of resolution for our camera and lens. All reported statistics refer only to droplets larger than 0.27 mm.

After stitching, the high resolution images were analyzed using custom image analysis algorithms we wrote in the MATLAB computational environment. In brief, each image was converted to binary via a standard image thresholding function, and then statistics about the size and centroid of each drop in the pattern were extracted and recorded. We emphasize that the algorithms automatically labeled and measured the several thousand discrete drops in a single pattern, without requiring any manual clicking on the drops by hand. Note that many drops were not circular in shape, so the equivalent diameter was calculated for each drop based on the detected area of the drop in pixels. In this manner, almost half a million individual droplets were analyzed across 72 individual spatter patterns. The size and spatial distributions extracted from the image analysis were then correlated with the weapon types and impact velocities as measured via high speed video.

Research Methodology: Double Blind Human Assessments

A representative set of 95 different bloodstains (47 generated by gunshot, 33 by blunt instrument impact, 9 by hand-flicking and 6 by dripping) were chosen and randomly numbered for inclusion in the study. To ensure that the study was performed in a double-blind fashion, one graduate student helped generate the bloodstain patterns experimentally and then the randomly numbered patterns were handled by another graduate student responsible for administering and compiling the analyst assessments. The process of stitching together the images produces slight artifacts in light intensity near the edges of each image, which we judged would be distracting to study participants. Accordingly, for the double-blind study a large-scale, commercial scanner was used to produce full size (1:1) grayscale photocopies. Our visual comparison of the original spatter patterns and the high-resolution photocopies confirmed that all droplets visible by the naked eye were faithfully reproduced in the photocopies provided to the study participants.

An additional five bloodstain patterns from the gunshot and blunt instrument spatter patterns were chosen at random, rotated 180 degrees, assigned separate numbers from the originals, and then included in the sample set to yield a total of 100 patterns. The study participants were not informed that the bloodstain patterns included any duplicates. This set of rotated patterns was included as a further control to test for consistency in participant responses.

Each study participant was provided the full-size, grayscale reproductions of all 100 bloodstain patterns, as well as standardized response forms, detailed instructions and definitions, and a questionnaire about their experience and qualifications as a bloodstain analyst. Each participant was asked to carefully study each bloodstain pattern and to assess what type of bloodstain pattern it was. The participants were provided with the following four categories of bloodstain spatter patterns:

"High velocity"	A bloodstain pattern resulting from an object impacting a blood source at 100 feet per second or greater. A typical example is spatter resulting from a gunshot.
"Medium velocity"	A bloodstain pattern resulting from an object impacting a blood source at roughly 25 feet per second. A typical example is spatter resulting from the impact of a blunt instrument swung by hand.
"Dripped/splashed "	A bloodstain pattern resulting from the impact either of blood droplets dripping by gravity, or resulting from a volume of blood that falls or spills onto a surface. A typical example is spatter resulting from blood drops dripping into a pool of blood.
"Cast-off"	A bloodstain pattern resulting from blood drops released from an object or limb while in motion. A typical example is spatter resulting from drops being "flung" off a bloody object or weapon such as a crow bar.

We emphasize that in utilizing the above definitions we are not advocating the use of the legacy terminology "medium velocity" or "high velocity" for characterization of spatter patterns, which as discussed previously has been quite controversial. Rather, they serve as short-hand here for gunshot and blunt instrument impact spatter patterns, which are unquestionably induced by impacts with highly disparate velocities. To provide some measure of the participants' confidence in each answer, we also asked them to mark whether they believed the stain was "definitely" or "probably" of a particular type.

Two cohorts of study participants were recruited for the study. The first cohort consisted of 10 qualified BPA analysts with extensive experience (several decades cumulatively) in bloodstain pattern analysis. Included in their mailed packet was a questionnaire so that they could anonymously self-report general statistics such as age, years of forensic experience, approximate number of BPA cases in which they have testified on in court, and their specific bloodstain pattern analysis training history (proficiency testing, education, etc.). The second cohort consisted of 10 student volunteers from the University of California Davis Forensic Science Graduate Program. These students were required to have no prior experience or training in BPA, but all underwent a brief training course (approximately 3 hours long) to provide them with some rudimentary background in assessment of bloodstain patterns. A two-day workshop was held for the students to complete their assessments, under close supervision to prevent collaboration.

Results: Quantitative Image Analysis

Since early investigators focused on the average size of the droplets within a spatter pattern, we first characterized the size distributions for each type of impact. Histograms of the spatter patterns indicated that the majority of the measurable droplets (larger than 0.27 mm) were smaller than 0.5 mm in diameter, with each histogram approximately following a lognormal distribution in drop diameter. Although the shapes of all the size distributions are qualitatively similar for both blunt instrument and gunshot spatter patterns, there are important differences. First, the total drop count varies dramatically between weapon types. The gunshot impacts yielded patterns with a total number of drops ranging from approximately 5000 to 12,000. The absolute number of droplets in the gunshot patterns roughly correlated with bullet velocity: note the faster-traveling .357 yielded about twice as many droplets as the slower moving .45. The droplet counts for the gunshots are generally higher than for the blunt instrument impacts, which typically yielded between 1000 to 6000 drops per impact. The major exception was the bat at full strength, which yielded around 40,000 droplets per pattern – a factor of four higher than the .357 caliber. This result strongly indicates that simply counting the total number of droplets in an impact spatter pattern does not help differentiate gunshot and blunt instrument impacts; in other words, a blunt instrument impacting with enough force easily generates many more droplets than a gunshot impact.

A second key (but more subtle) feature of the size distributions is that the mean droplet size differs between impact types. All of the blunt instrument impacts, including the bat at full strength, yielded mean drop sizes in the range 0.6 – 0.65 mm. In contrast, the gunshot impacts yielded mean drop sizes between 0.4 – 0.5 mm. This observation strongly corroborates one of the central hypotheses from early work on blood spatter pattern analysis: higher velocity impacts yield patterns with smaller drops. Note, however, that some of the error bars for the blunt instruments (specifically, the spatter patterns created by the hammer) actually overlap with the gunshot mean sizes. In other words, some of the blunt instrument spatter patterns had mean droplet sizes in the same range as the firearm spatter patterns.

The mean size is just one metric that can be extracted from the droplet size distributions. Many of the early recommendations for differentiating "medium" and "high" velocity spatter focused not only on the mean size but on the relative fractions of droplets within certain size ranges In general only a very small fraction of the droplets were larger than 3 mm in diameter. The gunshot impacts all yielded patterns with less than 0.1% "large" drops (> 3 mm), while the blunt instruments yielded patterns with between 0.2% to about 0.8% large drops. As for "medium-size" drops, between 1 and 3 mm in diameter, the blunt instrument impacts yielded a higher percentage of drops in this range (10% - 14%) compared to the gunshot impacts (5% or less). Finally, the vast majority of droplets, for both gunshot and blunt instrument impacts, fell in the "small" range of less than 1 mm in diameter (but greater than our 0.27 mm resolution cut-off). Approximately 85% to 90% of the droplets were less than 1 mm for the blunt instrument impacts, while 95% to 99% of the droplets generated by gunshot were less than 1mm. As before, the relative percentages were more reproducible between trial replicates for the gunshot impacts, as indicated by the relatively small error bars compared to the various blunt instrument impacts.

The above quantitative descriptions of the drop sizes were based on the entire spatter pattern; for example, the mean size was calculated based on every observable droplet in the pattern greater than 0.27 mm. Qualitatively, however, it appeared that large droplets tended to reside closer to the center of the pattern then at the periphery. We tested this hypothesis more quantitatively by assessing the size metrics as a function of distance from the centroid of the entire pattern. Our measurements indicate two main trends. First, the mean drop diameter is always larger for the blunt instrument impacts compared to the gunshots, for all values of *r*. (the distance from the center of the spatter pattern). Consistent with the mean drop diameters calculated over the entire pattern, the blunt instrument impacts yielded drop sizes that were typically 30 to 40% larger than the gunshot impacts for all distances from the pattern center. The second main trend is that the mean drop size varied with position in different manners for the different impact types. The 9 mm and .45 caliber bullets exhibited little sensitivity to the distance from the center, while the .357 magnum yielded a larger mean diameter close to the center of the pattern which decayed with distance. Close inspection of the spatter patterns suggests this result is partly an artifact due to the gunshot creating such a fine spray of overlapping drops. The blunt instrument impacts also yielded mean sizes that varied with position, albeit more weakly and in a more nonmonotonic fashion.

Since the relative fraction of "large", "medium" and "small" droplets seemed to differ considerably between gunshot and blunt instrument impacts when calculated over the entire pattern, we also investigated whether the relative fraction varied significantly with position in the pattern. Since each pattern contains multiple annuli, however, it is cumbersome to report three different size percentages as a function of position for the seven impact types. To simplify matters, we sought to define a single threshold size to differentiate between "large" and "small" droplets. We found that choosing the diameter 0.75 mm provided a clear differentiation between gunshot and blunt instrument impacts. The qualitative trends in plots of $f_{0.75}$ vs. r appear similar to those observed with the mean size: the blunt instruments consistently yielded a larger $f_{0.75}$ compared to the firearms. Although the qualitative trends for $f_{0.75}$ are similar to those observed with mean size, the quantitative contrast in $f_{0.75}$ between gunshot and blunt instruments is much more stark. Note that approximately 20 to 30% of the blunt instrument droplets were larger than 0.75

mm, regardless of position in the stain, whereas less than 10% of the droplets generated by gunshot were that large for values of $r > 10$ cm. In other words, the mean diameter for the blunt instruments are generally about 40% larger than the firearms over the range 2.5 cm $< r < 30$ cm, but $f_{0.75}$ for the blunt instruments was as much as 600% larger than for the firearms over the same range.

To highlight this difference in fraction of large droplets, and to avoid complications due to overlap near the center, Fig. 12 shows the f0.75 values at the distance of r=10 cm from the center for each weapon type. This figure clearly illustrates the large difference between the two categories of impacts, with the blunt instruments having an f0.75 value approximately 267% greater than the firearms. Importantly, note that the error bars (calculated as standard deviations over a minimum of three trial replicates) do not overlap between any of the gunshot or blunt instrument impacts. Table 2 presents the same observation calculated in a slightly different fashion, by averaging the mean drop size and f0.75 over all the trials for each class of impact (rather than individual weapon type). The mean drop size is on average 40% lower for blunt instruments compared to firearms, whereas the f0.75 (r = 10 cm) yielded an average difference of 267%. Tests of these metrics at other separation distances (between the impact and target surface) indicated that the general trends are robust with respect to distance. This observation suggests that f0.75 could be a useful metric for differentiating between the two impact types.

Results: Double-blind Human Assessment

With 20 individual participants, each of whom was asked to assess 100 bloodstain patterns, the double-blind study yielded 2000 unique assessments. Focusing first on the spatter patterns generated by gunshot, we see that the vast majority of the responses correctly indicated high velocity. Within the analyst cohort, 86% of the 480 responses correctly indicated high velocity, while 14% indicated insufficient information. Notably, only 1 of the 480 trained analyst responses incorrectly specified medium velocity, which corresponds to a 0.21% error rate. The student cohort performed similarly well for the gunshot spatter patterns: 93% of the responses correctly indicated high velocity.

In contrast, the accuracy rates for the spatter patterns generated by blunt instrument impacts were much lower (Fig. 3B). Only 41% of the 370 analyst assessments correctly indicated medium velocity; 38% incorrectly indicated high velocity, cast-off or dripped, while 21% indicated insufficient information. Of the incorrect assessments, the majority of responses indicated high velocity. The students actually performed better on the blunt instrument patterns: 61% of the 370 student assessments correctly indicated medium velocity, while 34% incorrectly indicated high velocity, cast-off or dripped and only 5% indicated insufficient information.

We sought to determine whether particular weapon types or distances were accurately assessed at different rates. To visualize trends in accuracy, we calculated a "weighted score" for each of the 100 individual bloodstain patterns. The weighted score penalized incorrect responses and explicitly accounted for the respondent's confidence level, using the following scheme: "Definitely" & correct = + 1.0; "Probably" & correct = + 0.5; "Insufficient information" = 0; "Probably" & incorrect = – 0.5; "Definitely" & incorrect = –1.0. Plots of the weighted scores for the gunshot and blunt instrument spatter patterns revealed two key trends. First, all of the gunshot spatter patterns created with velocity bullet impacts (.357 Magnum, .45 ACP, and 9mm Luger) received high weighted scores, suggesting that no particular firearm was disproportionately responsible for the small number of incorrect responses. The second key trend is that the blunt instrument patterns received a much wider range of weighted scores. The maximum observed score was +9.5, but the minimum score was –7, reflecting the large number of patterns incorrectly assessed with high confidence. Strikingly, of the 74 blunt instrument scores (37 patterns with 2 cohorts), a full third of them (25) received negative weighted scores.

We found no statistically significant correlations between amount of experience and assessment accuracy. This is perhaps not surprising, since the student cohort arguably performed as well as the highly experienced analyst cohort. Instead, we found that the vast majority of the negative scores for the blunt instrument impacts occurred in patterns generated at close distances, i.e., 12 inches or less. Examination of the mean size in these patterns revealed a statistically significant correlation between mean drop size and weighted score. In other words, patterns with smaller mean drop diameters received lower scores, while patterns with larger mean drop diameters received higher scores. This result suggests that the presence of lots of small drops was the main visual cue leading to incorrect assessments on the blunt instrument patterns.

Finally, a key advantage of our study design is that we were able to directly test for a consistency (i.e., reproducibility) in participant responses for the same pattern. Five patterns were chosen randomly, yielding a set of 4 blunt instrument patterns and 1 gunshot pattern. The patterns were rotated 180 degrees and provided a new random number; the participants were not informed nor appeared to notice that any duplicate patterns were inserted. Both the student and analysts cohorts had 100% consistency in their assessments of the one duplicated gunshot spatter pattern. In contrast, both cohorts were much less consistent for the duplicated blunt instrument spatter patterns. Of the 80 unique opportunities for the participants to provide a consistent response on the blunt instrument patterns (i.e., 4 patterns and 20 participants), an inconsistent assessment was provided 24 times. In other words, on average the participants failed to give the same assessment on the same pattern 30% of the time. This finding strongly suggests that the assessments of the blunt instrument spatter patterns had a pronounced stochastic aspect.

Implications for Policy and Practice

Our study has several implications for the forensic science community. First and foremost, we have established an image analysis methodology that yields hard data about bloodstain patterns. Much of the controversy about impact velocity assessment for spatter patterns is associated with the subjectivity inherent in simple visual examination of a pattern; in other words, two analysts might disagree about whether "most" of the droplets in a pattern are small or not. The image analysis methodology presented here provides an objective and rigorous means of quantifying the size and spatial characteristics of a spatter pattern. We emphasize that after the high-resolution photographs of the bloodstain are digitally stitched together, the software takes just a few seconds to automatically calculate the size and position of the many thousands of droplets present in a spatter pattern. We envision that this software could serve as a valuable tool for criminalists tasked with assessing bloodstain patterns found at crime scenes.

Second, our results indicate that the mean size and overall size distribution of droplets are suggestive – but not definitive – discriminants of impact velocity. The mean droplet size in patterns generated by blunt instrument was on average 40% larger than in patterns generated by gunshot, but some of the blunt instrument and gunshot spatter patterns had equivalent mean size and size distributions. Instead, our quantitative results suggest that one such spatially-based metric, $f_{0.75}$ evaluated at a distance r = 10 cm from the pattern centroid, is a statistically significant discriminant of impact velocity: we found on average a 267% difference in $f_{0.75}$ between gunshot and blunt instrument spatter patterns.

Finally, our double-blind study helps clarify the nature of the controversy surrounding impact velocity assessment for spatter patterns: the key problem is that, for small impact-to-target distances, blunt instrument impacts can yield patterns that look like high velocity spatter patterns. Moreover, the high rate of inconsistent assessments provided by the participants when presented with the same bloodstain pattern twice appears to corroborate the NRC criticism about subjectivity in analyst interpretation of bloodstain patterns.

Our study leads to two key recommendations. First, bloodstain pattern analysts should indeed be cautious in attributing an impact velocity to a spatter pattern of unknown origin, especially in the absence of secondary indicia (such as bullet casings or bloody blunt instruments found at the crime scene). In situations where such contextual information is unavailable, analysts should be aware of the key asymmetry revealed by our study: spatter patterns generated by gunshot are readily identifiable, but spatter patterns generated by blunt instrument impact, especially at small distances, can also look like a gunshot spatter pattern. The second key recommendation is that bloodstain analysis community should strongly consider supporting the continued development of objective and quantitative methodologies for assessment of spatter patterns. We believe the digital image analysis methodology presented here will serve as a framework for improving quantitative assessments of bloodstain patterns under the more challenging conditions found in practice.

Executive Summary Bibliography

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Part 1: Quantitative Differentiation of Spatter Patterns Resulting from Bullet and Blunt Force Impacts

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ABSTRACT

Bloodstain pattern analysis (BPA) provides significant evidentiary value in crime scene interpretation and reconstruction, but many aspects of BPA are controversial due to the heavy reliance on qualitative and subjective interpretation. For example, the differentiation between so-called "medium" and "high" velocity impact spatter patterns – legacy terminology typically associated with blunt instrument and gunshot impacts, respectively – has traditionally relied on visual assessment of the average drop size in the pattern. Because this methodology is subjective and susceptible to context bias, most BPA organizations recommend against even attempting to describe the velocity that creates a spatter pattern, despite the clear forensic value of such determinations in crime scene interpretation. In this work, we develop a quantitative methodology using digital image analysis techniques to differentiate medium and high velocity impact spatter patterns in an objective manner. Bloodstain spatter patterns were created under controlled conditions by impacting either blunt instruments or bullets into blood-soaked sponges. The impact velocities were determined using high-speed video, and the resulting spatter patterns were digitally imaged at high resolution then analyzed using custom image analysis algorithms. Our analysis of 72 unique spatter patterns, comprising more than 490,000 individual droplets, indicates that the mean drop size in a gunshot spatter pattern is at most 30% smaller than the mean drop size in blunt instrument patterns. In contrast, we demonstrate

that the spatial distribution of the droplets – i.e. their density as a function of position in the pattern – significantly differs between bullet and blunt instrument patterns, with densities as much as 600% larger for bullet impacts. Our findings suggest that quantitative metrics involving the spatial distribution of droplets within a spatter pattern can be useful for objective differentiation between blunt instrument and gunshot spatter patterns.

INTRODUCTION

Bloodstain pattern analysis (BPA) is a key tool in forensic science, aiding in crime scene reconstructions and helping to establish other elements of criminal acts (1,2). Some aspects of BPA are well understood by the community and are discussed in detail in standard texts for BPA. For example, arguably the most well-known BPA technique involves determination of the angle of impact of a droplet onto a surface, and using triangulation for several droplets to determine the point of origin (1,3). This triangulation methodology has been investigated extensively (4-6), with studies that provide rigorous assessments of error rates for both angle of impact (7) and point of origin (8).

Other aspects of BPA, however, remain less well understood. One important but controversial aspect involves the characterization of "impact spatter" patterns. Specifically, a common request made of BPA experts is to assess whether a particular spatter pattern was generated as a result of a blunt instrument impact or a more energetic impact, e.g., a gunshot. Early studies in the 1960s, including the seminal work by H.L. MacDonell, made a distinction between what they defined as "medium velocity" and "high velocity" impact spatter. MacDonell's original classification of bloodstain patterns stated the following (1):

Medium: "…many small droplets of 1/8 inch in diameter or smaller"

High: "…an extremely high percentage of very fine specks of blood…essentially all under 1/8 inch diameter"

By the early 2000s, the delineation between the two types of spatter had changed little; James *et al*. state the following as the conventional definitions of "medium" and "high" velocity impact spatter in their text on BPA (9):

> Medium: “a force with a velocity in the range of 5 to 25 ft/sec. (1.5-7.6 m/sec.). The diameter of resulting stains are in the size range of drops 1 to 3 mm...”
>
> High: “a force with a velocity of greater than 100 ft/sec. (30.5 m/sec.). The diameters of the spatters are predominately less than 1 mm...”

Despite the widespread use of these definitions for almost 4 decades, however, over the past decade the terminology has fallen out of favor. The differentiation between medium and high velocity was increasingly viewed as subjective, with great risk of contextual bias affecting the assessment. In their assessment of the state of blood pattern analysis, the National Research Council noted that “some experts extrapolate far beyond what can be supported” and that “…many bloodstain pattern analysis cases are prosecution driven or defense driven, with targeted requests that can lead to context bias” (10). Consideration of the above definitions provides insight on the underlying source of controversy: note that the definitions for medium and high velocity are not mutually exclusive. In MacDonell’s definitions, both medium and high velocity impacts are defined as having many small droplets under 1/8 inch. The differentiation thus hinges on an individual analyst’s opinion of what constitutes “an extremely high percentage.” Likewise, the mid-1990s IABPA definition requires “a majority” of droplets be within a certain size range. However, a single spatter pattern can contain hundreds or thousands of droplets, so in practice the differentiation hinged on the analyst’s subjective impression of how many sufficiently small drops are present within a pattern. It is worth emphasizing that the National Research Council stated in their 2009 report that, "In general, the opinions of bloodstain analysts are more subjective than scientific" (10).

Because of the controversy, key BPA organizations, such as the Scientific Working Group on BPA (SWGSTAIN), have removed velocity classifications from their list of recommended terminology (11). Typically impact spatter is now only differentiated with respect to the overall shape of the pattern, including "patterns with no linear orientation" or "with radiating distribution" (3). These aspects describe only the overall morphology of the pattern and do little to identify how the pattern was generated.

Although the official recommendations regarding the assessment of medium and high velocity patterns have changed over the past decade, there has been notably little published research to support the current recommendations or any particular hypothesis. To our knowledge, the only recent quantitative work on spatter patterns was performed by Karger *et al.*, who investigated spatter generated by shooting cattle at close range (12, 13). They provided histograms characterizing the relationship between drop size and distance traveled in the case of back spatter from close-range gunshots. Although this work helped characterize gunshot impact spatter, little insight was provided on how to differentiate gunshot spatter from spatter generated by blunt instrument impacts. Despite the clear need for such differentiations, to date it remains unclear under what conditions, if any, that gunshot and blunt instrument spatter patterns may be accurately differentiated. In 2011 the research subcommittee of SWGSTAIN prepared a list of current research needs for bloodstain pattern analysis; the first item on their list was "Research that would minimize ambiguity in the characterization of small stain blood spatter patterns."

In this paper, we develop a quantitative methodology to help differentiate spatter patterns generated by gunshot or blunt instrument impacts. Spatter patterns were created under controlled conditions by various caliber bullets and different blunt instruments, with impact velocities measured precisely using high speed video. Custom image analysis algorithms were developed to automatically and rapidly extract quantitative measurements of the size distribution and spatial distributions of individual droplets within a spatter pattern. In this manner we measured approximately half a million individual droplets in 72 unique spatter patterns. A key result is that the mean size of droplets generated by gunshot is at most 30% smaller than in blunt instrument spatter, but that a $f_{0.75}$, a spatially-dependent metric for fraction of droplets greater than 0.75 mm in diameter, is 600% greater for blunt instrument spatter. Our findings suggest that quantitative metrics based on the spatially-dependent size distribution of droplets within a spatter pattern can provide a more robust and objective means for differentiating spatter patterns generated by gunshot or blunt instrument impact.

STUDY DESIGN AND METHODOLOGY

Materials and Methods

All spatter patterns examined here were generated under controlled conditions in an underground firing range at the Sacramento County Laboratory of Forensic Sciences. Porcine (pig) blood was used to generate the spatter patterns; one gallon of fresh blood was mixed with 360 ml of a 33% sodium citrate anticoagulant solution and refrigerated until use. Immediately before each experiment, the blood was heated to human body temperature (37°C) by placing the container of blood into a circulating waterbath. To generate the impact spatter patterns, a sponge (Ace Medium All Purpose, yellow polyesthor, 3.5" deep, 4.5" wide and 2.5" tall) was soaked in blood until it adsorbed precisely 1.7 oz (48 g) of blood. Sponges were chosen as a model system rather than live animal specimens because of the logistical challenges associated with animal experimentation; moreover, sponges allow the amount of blood present and available for spattering in each impact experiment to be held constant so that the projected area of each weapon type dictated how much blood interacted with the weapon. After addition of the blood, the sponge was then immediately placed on a wooden pedestal (a plywood platform at waist height affixed to a 4x4 vertical wooden beam) to be either hit with a blunt weapon (swung by hand) or shot with a firearm (Fig. 1). All firearms were shot at a distance of six feet away from the sponge to prevent complications associated with gunpowder residue. Standard white plotter paper acted as the vertical target surface and was placed at a specified distance L from the impact site. For the firearm experiments, the target paper was placed behind the sponge to catch the spatter; the bullet necessarily also passed through the paper, leaving a bullet hole. In contrast, for the blunt weapon experiments, with the exception of the hammer, the target paper was placed to the left of the sponge, since most of the spatter travelled in a direction orthogonal to the weapon impact. The target paper was placed behind the sponge for the hammer since we found more spatter travelled forward for this weapon, presumably because of the symmetric circular shape of the impacting surface compared to the baseball bat and the crowbar. In all cases the sponge was loosely tied with a piece of string to the wooden platform to prevent the sponge from flying into the paper target following the impact. For each specified sponge-target distance, we conducted at least three replicates using three different caliber firearms (.357, 9 mm, .45) and three blunt instrument types (bat, hammer, crowbar) (Table 1). Note that one of the weapons, the baseball bat, was swung either at “half-strength” or “full-strength” by an adult male volunteer, with the qualitative magnitude of the strength characterized by the volunteer.

Video Analysis and Determination of Impact Speed

To measure the precise impact velocity, each impact was filmed using a Phantom V7.3 camera recording at 10,000 to 15,000 frames/second (depending on the weapon type). Fig. 2 shows a representative time lapse obtained from the high speed video of a bullet impact, while Fig. 3 represents a representative impact by a blunt instrument. For each blunt weapon, solid black circles printed on paper (diameter = 1 cm) were taped to the impacting end, which simplified the image analysis for tracking the impact velocity of the weapon.

Impact velocities were calculated by tracking the change in position of either the bullet or blunt instrument between subsequent images captured at a known frame rate. Fig. 4a shows average bullet velocities for the three firearms. As expected, the .357 bullets travelled approximately 425 m/s, considerably faster than the 9 mm (350 m/s) or .45 (250 m/s); these velocities are consistent with published standards (15). Note that the impact and penetration through the sponge had little effect on the bullets, which continued onward without any measurable decrease in the velocity, and accordingly only a single value of velocity is reported for each type of bullet. Velocity measurements were double checked with a bullet chronograph; the velocities measured via the chronograph and image analysis were found to agree within 2%.

In contrast, the velocity of the blunt instruments had a strong dependence on the instantaneous position, since the weapons necessarily reversed direction following the impact (due to recoil). Fig. 4b shows representative plots of the absolute magnitude of the velocity for the blunt instruments. Prior to impact (i.e., times less than zero), the absolute velocity was relatively large, followed by a precipitous decrease in velocity as the instrument impacted the sponge and wooden platform. Fig. 4b demonstrates that the blunt instrument impacts were primarily inelastic; the recoil velocities were on average about one third of the incoming velocities (suggesting the coefficient of restitution was approximately 0.3). For the purpose of this work, we are interested in the 'impact velocity', which is defined here as the peak velocity observed during the 5 ms prior to impact. As indicated in Fig 4B, the impact velocities of the blunt instruments were all an order of magnitude smaller compared to the bullet velocities. The crowbar, hammer and bat (half-strength) were typically on the order of 10 to 15 m/s, while the bat (full strength) was roughly a factor of two faster at about 25 m/s.

Digital Image Analysis of the Spatter Patterns

After allowing them to dry, each spatter pattern was photographed at high resolution to visualize as many of the small drops as possible. The patterns were photographed in approximately 1 square foot sections, using a Canon EOS 7D digital (18.0 Mega Pixel) SLR camera and an EF-S 60mm f/2.8 Macro lens. The patterns were illuminated for photography using four large flood lights which were positioned to provide uniform illumination. In this manner each spatter pattern generated between 16 and 25 individual images. The images were subsequently "stitched" together as seamlessly as possible in Photoshop to create one large image of the entire pattern.

Because the digital images of the spatter patterns were the primary experimental observations obtained in this work, we took care to assess the effect of various image artifacts. A first crucial question is: what was the smallest resolvable drop size? With our sensor and macro lens, each pixel in an image was 0.06 mm wide. Thus, in theory a droplet as small as 0.06 mm in diameter could be resolved. Note, however, slight differences in the background illumination and/or the color of the drop could affect whether a particular pixel in an image was sufficiently dark to be counted. To be conservative, therefore, we operated under the assumption that all distances could be measured only to within ± 2 pixels, so that droplets had to be comprised of more than 4 pixels to be counted. For our setup this minimum number of pixels corresponds to a drop with diameter of 0.27 mm, which was thus chosen as the practical limit of resolution for our camera and lens. In other words, all quantitative metrics reported here (such as the mean drop size, spatial density, etc.) only consider droplets with equivalent diameters of 0.27 mm or larger.

A second possible concern involved lens distortion due to the spherical shape of the lens. Photoshop provides a built-in option to correct lens distortion, but comparison of identical images with or without lens correction indicated that the correction algorithm adversely affected the resolution of the image; many of the smaller drops disappeared upon running the correction. We concluded that the effect of the lens distortion on image analysis was negligible, with a maximum difference of about 4 pixels (0.25 mm) in drop position when comparing the same drop photographed at the edge versus the center of the field of view. This deviation is negligible compared to the width of the spatter patterns (approximately 1 meter wide).

After stitching, the high resolution images were analyzed using custom image analysis algorithms in the MATLAB computational environment. In brief, each image was converted to binary via a standard image thresholding function, and then statistics about the size and centroid of each drop in the pattern were extracted and recorded. We emphasize that the algorithms automatically labeled and measured the several thousand discrete drops in a single pattern, without requiring any manual clicking on the drops by hand. Note that many drops were not circular in shape, so the equivalent diameter was calculated for each drop based on the detected area of the drop in pixels. An important caveat is that overlapping droplets, i.e., individual droplets which impacted the target paper sufficiently close to at least partially overlap, were treated by the software as a single droplet. In other words, we report here the drop distributions "as observed on the surface" rather than attempting to reconstruct the drop distributions "as generated by the impact." Following this procedure, almost half a million droplets were analyzed across 72 individual spatter patterns (cf. Table 1). The size and spatial distributions extracted from the image analysis were then correlated with the weapon types and impact velocities as measured via high speed video.

RESULTS

Droplet Size Distributions

Representative examples of gunshot and blunt instrument spatter patterns (with L = 12 in.) are shown in Fig. 5. Note that because of space limitations only a small fraction of each spatter pattern is reproduced here; the full images are available in the supplementary material. Each row of images in Fig. 5 shows, respectively from left to right, a low magnification image, a higher magnification image, and a false-color image illustrating output from our image analysis code; the false colors correspond to different size thresholds. The first row (Fig 5a-c) shows a representative spatter pattern resulting from a 9 mm bullet impact. This example is typical of the spatter patterns generated by gunshot because most of the droplets are small, indicated by all the red drops, with very few drops 1 to 3 mm in size, indicated by the blue. The middle row (Fig. 5d-f) shows a representative spatter pattern generated by impact of a baseball bat at "half-strength". In contrast to the previous pattern, the half-strength bat impact yielded more of the larger drops (blue) and fewer small drops (red). Moreover, the total number of drops was smaller and the overall pattern more sparse. The bottom row (Fig. 5g-i) again shows another representative spatter pattern generated by a baseball bat, but with a much higher impact velocity ("full-strength"). Qualitatively, this spatter pattern is more similar to the 9mm pattern. The bat at full strength yielded a high number of small drops (red), a lower number of large drops (blue), and overall a high concentration of drops. We reiterate that the smallest "yellow" droplets (< 0.27 mm) were not reliably measured during the image analysis and were thus excluded from the quantitative analyses, but are nonetheless shown here to convey how representative spatter patterns appeared. The key observation in Fig.5 is that there is stark difference between the 9mm and "half-strength" bat spatter patterns, but a more subtle difference between the 9mm and "full-strength" bat spatter patterns.

Since early investigators focused on the average size of the droplets within a spatter pattern, we first characterized the size distributions for each type of impact. Representative histograms of the drop sizes within three different patterns are presented in Fig. 6a-c. The qualitative trends shown in Fig. 5 are seen quantitatively in Fig. 6: for each type of pattern, the majority of the droplets were smaller than 0.5 mm in diameter, with each histogram approximately following a lognormal distribution in drop diameter. Although the shapes of all three distributions are qualitatively similar, there are important differences. First, the total drop count is dramatically different (as indicated by the vertical scale on each plot). The 9mm yielded about 10,000 droplets, the bat at half-strength yielded only 4,600 drops, while the bat at full-strength yielded about 45,000 droplets – a full order of magnitude more.

To assess whether the results regarding total number of drops shown in Fig. 6 are reproducible, we measured the total number of droplets in each spatter pattern. The results are presented in Fig. 7, which shows the total number of drops per pattern for all impact types at L=12 inches, averaged over three trial replicates. The gunshot impacts yielded patterns with a total number of drops ranging from approximately 5000 to 12,000. The absolute number of droplets in the gunshot patterns roughly correlated with bullet velocity: note the faster-traveling .357 yielded about twice as many droplets as the slower moving .45 (cf. Fig. 4a). The droplet counts for the gunshots are generally higher than for the blunt instrument impacts, which typically yielded between 1000 to 6000 drops per impact. The major exception was the bat at full strength, which yielded around 40,000 droplets per pattern – a factor of four higher than the .357 caliber. This result strongly indicates that simply counting the total number of droplets in an impact spatter pattern does not help differentiate gunshot and blunt instrument impacts; in other words, a blunt instrument impacting with enough force easily generates many more droplets (larger than 0.27 mm) than a gunshot impact, at least under the conditions used in this study.

A second key (but more subtle) feature of the representative histograms in Fig. 6 is that the mean droplet size differs between impact types. Fig. 8 shows the mean droplet diameter per pattern, averaged over three trial replicates, as a function of impact velocity (i.e., corresponding to each specific impact type). Here we see a more distinct difference between the two categories of impacts (gunshot and blunt instrument) than was observed for the total number of drops per pattern. All of the blunt instrument impacts, including the bat at full strength, yielded mean drop sizes in the range 0.6 – 0.65 mm. In contrast, the gunshot impacts yielded mean drop sizes between 0.4 – 0.5 mm. This observation strongly corroborates one of the central hypotheses from early work on blood spatter pattern analysis: higher velocity impacts yield patterns with smaller drops. Note, however, that some of the error bars for the blunt instruments (specifically, the spatter patterns created by the hammer) actually overlap with the gunshot mean sizes. In other words, some of the blunt instrument spatter patterns had mean droplet sizes in the same range as the firearm spatter patterns.

The mean size is just one metric that can be extracted from the droplet size distributions. Many of the early recommendations for differentiating "medium" and "high" velocity spatter focused not only on the mean size but on the relative fractions of droplets within certain size ranges (e.g., James *et al.* (9)). Fig. 9 shows the relative percentages of drops larger than 3 mm, between 1 mm and 3mm, and smaller than 1mm for each type of impact as a function of impact velocity. Focusing first on large drops (Fig. 9a), we see that in general only a very small fraction of the droplets were larger than 3 mm in diameter. The gunshot impacts all yielded patterns with less than 0.1% "large" drops (> 3 mm), while the blunt instruments yielded patterns with between 0.2% to about 0.8% large drops. Fig. 9b shows the percentage of "medium-size" drops, between 1 and 3 mm in diameter, as a function of impact velocity. Again, the blunt instrument impacts yielded a higher percentage of drops in this range (10% - 14%) compared to the gunshot impacts (5% or less). Fig. 9c shows the percentage of "small" drops less than 1 mm in diameter (but greater than our 0.27 mm resolution cut-off). Notably, the vast majority of droplets fell in this range for both gunshot and blunt instrument impacts. Approximately 85% to 90% of the droplets were less than 1 mm for the blunt instrument impacts, while 95% to 99% of the droplets generated by gunshot were less than 1mm. As before, the relative percentages were more reproducible between trial replicates for the gunshot impacts, as indicated by the relatively small error bars compared to the various blunt instrument impacts.

These size statistics again corroborate an early central hypothesis, that "most" of the droplets in a high velocity spatter pattern will be smaller than 1 mm. Our measurements provide a quantitative measure of what "most" means: we find that approximately 95% or more of the droplets in a gunshot spatter are less than 1 mm, while only 90% or less are this small for blunt instrument spatter patterns. Note, however, that the overlapping error bars between the hammer spatter patterns and the firearm patterns indicates that some blunt instrument spatter patterns also exceed 95% of droplets less than 1 mm, precluding the use of this number as a hard criterion for determination of impact velocity. In other words, some blunt instrument spatter patterns contain "mostly" small droplets in a manner similar to gunshot spatter patterns.

Spatial Distributions and Analysis

All of the above quantitative descriptions of the drop sizes were based on the entire spatter pattern; for example, the mean size was calculated based on every observable droplet in the pattern greater than 0.27 mm. Qualitatively, however, it appeared that large droplets tended to reside closer to the center of the pattern then at the periphery. We tested this hypothesis more quantitatively by assessing the size metrics as a function of distance from the centroid of the entire pattern. Fig. 10 illustrates this process conceptually. Here a representative spatter pattern is segregated into annuli 2.5 cm wide that radiate outward from the pattern center. The exact position of the center was defined as the average position of every droplet greater than 0.27 mm in the entire pattern (i.e., the centroid was defined as the first moment of position of all observable droplets). Within each annulus, the mean drop size, the number of drops in various drop size groupings, and the overall drop density (drops per unit area) were calculated.

Focusing first on the average size, Fig. 11a shows the mean droplet size as a function of distance *r* from the pattern centroid. Note that each point is average over three trial replicates; the error bars (calculated as the standard deviation) thus represent variability between trials. Two main trends are apparent in Fig. 11a. First, the mean drop diameter is always larger for the blunt instrument impacts compared to the gunshots, for all values of *r*. Consistent with the mean drop diameters calculated over the entire pattern (cf. Fig.. 8), the blunt instrument impacts yielded drop sizes that were typically 30 to 40% larger than the gunshot impacts for all distances from the pattern center. The second main trend is that the mean drop size varied with position in different manners for the different impact types. The 9 mm and .45 caliber bullets exhibited little sensitivity to the distance from the center, while the .357 magnum yielded a larger mean diameter close to the center of the pattern which decayed with distance. Close inspection of the spatter patterns suggests this result is partly an artifact due to the gunshot creating such a fine spray of overlapping drops. Note that our image analysis algorithms necessarily treated partially overlapping smaller droplets as a single larger droplet. Fig. 11a indicates that this overlapping effect is most pronounced near the center of the pattern, consistent with our qualitative observations. The blunt instrument impacts also yielded mean sizes that varied with position, albeit more weakly and in a more nonmonotonic fashion.

Since the relative fraction of “large”, “medium” and “small” droplets seemed to differ considerably between gunshot and blunt instrument impacts when calculated over the entire pattern (cf. Fig. 9), we also investigated whether the relative fraction varied significantly with position in the pattern. Since each pattern contains multiple annuli, however, it is cumbersome to report three different size percentages as a function of position for the seven impact types. To simplify matters, we sought to define a single threshold size to differentiate between "large" and "small" droplets. After trying several thresholds, we found that choosing the diameter 0.75 mm provided a clear differentiation between gunshot and blunt instrument impacts. The results of this approach are presented in Fig. 11b, which shows the fraction of drops that have a diameter of 0.75 mm or greater (defined as $f_{0.75}$) as a function of distance from the droplet center. The qualitative trends look similar to those observed with the mean size (cf. Fig. 11a); the blunt instruments consistently yielded a larger $f_{0.75}$ compared to the firearms. Although the qualitative trends for $f_{0.75}$ are similar to those observed with mean size, the quantitative contrast in $f_{0.75}$ between gunshot and blunt instruments is much more stark. Note that approximately 20 to 30% of the blunt instrument droplets were larger than 0.75 mm, regardless of position in the stain, whereas less than 10% of the droplets generated by gunshot were that large for values of $r > 10$ cm. In other words, the mean diameter for the blunt instruments are generally about 40% larger than the firearms over the range 2.5 cm $< r <$ 30 cm, but $f_{0.75}$ for the blunt instruments was as much as 400% larger than for the firearms over the same range. Again, the .357 magnum has a higher $f_{0.75}$ close to the center, presumably due to the large amount of overlapping that occurs. For positions $r > 10$ cm this artifact diminished, and $f_{0.75}$ accordingly decreased.

To highlight this difference in fraction of large droplets, and to avoid complications due to overlap near the center, Fig. 12 shows the $f_{0.75}$ values at the distance of r=10 cm from the center for each weapon type. Also shown are analogous results for different choices of the threshold diameter (0.5 mm and 1.0 mm). Figure 12 clearly illustrates the large difference between the two categories of impacts, with the blunt instruments having an $f_{0.75}$ value approximately 267% greater than the firearms. Importantly, note that the error bars (calculated as standard deviations over a minimum of three trial replicates) do not overlap between any of the gunshot or blunt instrument impacts. Table 2 presents the same observation calculated in a slightly different fashion, by averaging the mean drop size and $f_{0.75}$ over all the trials for each class of impact (rather than individual weapon type). The mean drop size is on average 40% lower for blunt instruments compared to firearms, whereas the $f_{0.75}$ (r = 10 cm) yielded an average difference of 267%. This observation suggests that $f_{0.75}$ could be a useful metric for differentiating between the two impact types.

To assess whether the observed differences are statistically significant, we used standard ANOVA methodology to test the null hypothesis that the means are equivalent. These results are shown in Fig. 13 and Table 3, which show the differences in average drop diameter and $f_{0.75}$ for the generic weapon types and specific weapon types respectively. As shown in Fig. 13a, the mean drop diameter for the entire collection of gunshot spatter patterns at L = 12 inches, averaged together, was approximately 0.45±0.05 mm, while for the blunt instrument patterns the mean diameter was approximately 0.60±0.10 mm. These distributions differ in a statistically significant sense ($p = 1.51 \cdot 10^{-5}$). Likewise, the values of $f_{0.75}$ differ by an even greater margin: the gunshot patterns yielded $f_{0.75}$ = 0.06±.04, while the blunt instrument patterns yielded $f_{0.75}$ = 0.23±.10. Again, these means differ in a statistically significant sense ($p = 7.91 \cdot 10^{-8}$).

Comparisons of specific weapon types (rather than generic weapon types) demonstrates that the mean drop diameter did not always exhibit a statistically significant difference between weapon types, whereas our observed values of $f_{0.75}$ did. The p values for each specific weapon comparison, using the 0.45 caliber distribution as the reference, are shown in Table 3. Setting the threshold at $p \leq 0.05$ to reject the null hypothesis, we see that the mean drop diameter does not always differ significantly for each blunt instrument type: note that the comparison of 0.45 versus the hammer yields p = 0.077. This lack of statistically significant difference is consistent with the results shown in Fig. 8, where the error bars for the hammer patterns are seen to overlap with the firearm patterns. In contrast, the comparisons for $f_{0.75}$ for with all four blunt instrument types yielded p values sufficiently small to reject the null hypothesis (again, consistent with the lack of overlapping error bars in Fig. 12). Similar comparisons using the other firearm types as the reference yielded analogous results. We conclude that, at least for our experimental conditions at L =12 inches, $f_{0.75}$ is a better discriminant between weapon types than the mean drop diameter.

Effect of Separation Distance (L)

All of the results and calculations to this point have focused on a separation distance of one foot (i.e., L = 12 inches, cf. Fig. 1). A key question is whether the trends reported for mean size and fraction of large droplets are conserved for different values of L. To address this question, we systematically varied L and repeated the experimental procedures and analysis. Fig. 14 presents representative examples of how the distance L affects some of the quantitative metrics studied here. First, Fig. 14a compares the total number of drops in a pattern as a function of L for the .45, .357 magnum, bat (full-strength), and crowbar. For all four weapons the total number of drops generally decreases as L increases. This behavior is consistent with the well-known phenomenon that the smaller an object is, the smaller a distance it can travel before aerodynamic drag appreciably inhibits its velocity (16); in other words, at larger distances, less of the smallest droplets were able to reach the target surface. Similar types of weapons, however, exhibited different sensitivity to L. The .45 exhibited a 3-fold decrease in the number of drops as L doubled from 12 to 24 inches, while the .357 magnum exhibited a 20 fold decrease in the total number of drops as L increased from 12 to 48 inches. Moreover, there was much overlap in the total number of droplets when comparing gunshots and blunt instruments, regardless of the separation distance. For example, the baseball bat (full-strength) at 36 inches has a similar value as the .357 magnum at both 12 and 24 inches.

Fig. 14b compares the overall mean drop diameter of a pattern in relation to target distance, L, again for the .45, .357 magnum, bat (full-strength), and crowbar. A key trend is that the mean size is relatively insensitive to the separation distance, at least over the distances tesed here. Notably, the mean diameters do not overlap between the two different weapon types. Finally, Fig. 14c shows $f_{0.75}$ (r = 10 cm) for various separation distances, again for the .45, .357 magnum, bat (full-strength), and crowbar. Similar to the mean size, the fraction of large droplets is relatively insensitive to separation distance. Importantly, the $f_{0.75}$ value is distinctly different between the gunshots and blunt instrument impacts over the separation distances tested. It is also apparent that the results shown in Table 2 are reflected over a wide range of *L*, i.e., $f_{0.75}$ differs more significantly than the mean diameter between gunshot and blunt instrument impacts.

DISCUSSION

Our study has several implications for the forensic science community. First and foremost, we have established an image analysis methodology that yields hard data about bloodstain patterns. Much of the controversy about impact velocity assessment for spatter patterns is associated with the subjectivity inherent in simple visual examination of a pattern; in other words, two analysts might disagree about whether "most" of the droplets in a pattern are small or not. The image analysis methodology presented here provides an objective and rigorous means of quantifying the size and spatial characteristics of a spatter pattern. We emphasize that after the high-resolution photographs of the bloodstain are digitally stitched together, the software takes just a few seconds to automatically calculate the size and position of the many thousands of droplets present in a spatter pattern. We envision that this software could serve as a valuable tool for criminalists tasked with assessing bloodstain patterns found at crime scenes. In particular, this image analysis methodology could provide a means of objective spatter pattern assessment without the possibility of contextual bias. For example, crime scene pictures of a spatter pattern could be sent to a separate facility where the images are analyzed in a blind fashion without any contextual information. This procedure would address a key criticism of the NRC report, since it would substantially minimize the influence of contextual bias.

The second key implication of our results is that the mean size and size distribution of droplets are suggestive – but not definitive – discriminants of impact velocity. The mean droplet size in patterns generated by blunt instrument was on average 40% larger than in patterns generated by gunshot. Likewise, on average 95% or more of all droplets in a gunshot spatter pattern were smaller than 1 mm, while on average less than 90% of droplets in blunt instrument patterns were smaller than 1 mm. These results suggest that an analyst faced with a spatter pattern of unknown origin could examine these size statistics to help assess the probable impact velocity. However, our results also indicate that under some conditions blunt instrument impacts yield spatter patterns with mean drop sizes and fraction of small droplets that mimic those observed for gunshot spatter patterns. Assigning an impact velocity to a pattern of unknown origin based solely on the overall spatter pattern size could be problematic, especially in the absence of secondary indicia (e.g., weapons found at the crime scene).

A third key implication of our study, however, is that other metrics based on the spatial organization of droplets within the pattern could be of great forensic value. Since our software automatically measures the size and position of every droplet within the spatter pattern, it is straightforward to determine mean size or droplet density as a function of position within the pattern. Our results suggest that one such spatially-based metric, $f_{0.75}$ evaluated at a distance r = 10 cm from the pattern centroid, is a statistically significant discriminant of impact velocity. We found on average a 267% difference in $f_{0.75}$ between gunshot and blunt instrument spatter patterns, which is considerably larger than the average 40% difference in mean size. Moreover, none of the error bars (evaluated as standard deviations over three trial replicates) overlapped between any of the firearm or blunt instrument types (cf. Fig. 12b). This general trend was observed over a wide range of impact-to-target distances. These results suggest that $f_{0.75}$ might be a particularly useful quantitative and unambiguous metric for assessments of impact velocity.

CONCLUSIONS

We have developed an image analysis methodology to rapidly quantify the size and position of all droplets present within a spatter pattern, and we used this methodology to study almost 500,000 droplets in 72 unique spatter patterns. Our study suggests that the legacy methodology of characterizing impact spatter patterns based on the average drop size is suggestive but not definitive. Instead, spatially-based size metrics (such as $f_{0.75}$) might serve as rigorous discriminants of impact velocity for spatter patterns of unknown origin.

We emphasize that all of the bloodstain patterns studied here were generated under controlled laboratory conditions. Bloodstain patterns generated at actual crime scenes will likely have many complicating factors, including obstruction by clothing or other objects, superposition of multiple spattering events, and complications due to spatter landing on fabric or other non-uniform surfaces. These aspects, and their influence on the resulting spatter patterns, need further study. The key point here isn't the specific numeric value of the size threshold (e.g., 0.75 mm) found to be optimal for our experimental conditions, but rather the methodology itself. Further validation and selection of the best cutoff should be based upon analysis of actual crime scene spatter patterns. The work presented here thus serves as a framework for developing quantitative and objective means of assessing bloodstain patterns under the more challenging conditions found in practice.

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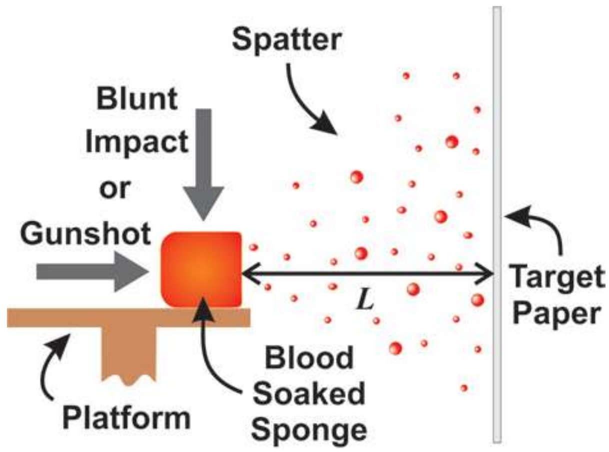

Figure 1: Experimental apparatus consisting of a wooden stand on which a sponge soaked in porcine blood was placed and tied down. A frame holding the target surface was placed a distance *L* away from the sponge, which was either shot or hit with various weapons.

Firearm	Caliber	Bullet Type	Bullet Weight	Total Droplets Analyzed
Colt pistol	0.45	FMJ	230 grains	37,617
Sig Sauer pistol	9 mm	FMJ	115 grains	40,721
Smith & Wesson revolver	0.357	JHP	110 grains	103,556

Blunt Weapon		Weight	Length	Total Droplets Analyzed
Bat	"full-strength"	28 oz	34 in	256,677
	"half-strength"			12,007
Hammer		16 oz	13 in	15,062
Crowbar		51 oz	23.5 in	28,392

Table 1: A list of firearms and blunt weapons used in this study, along with information about the bullets, blunt weapons, and the total number of droplets generated by each weapon in aggregate. FMJ = full metal jacket; JHP = jacketed hollow point.

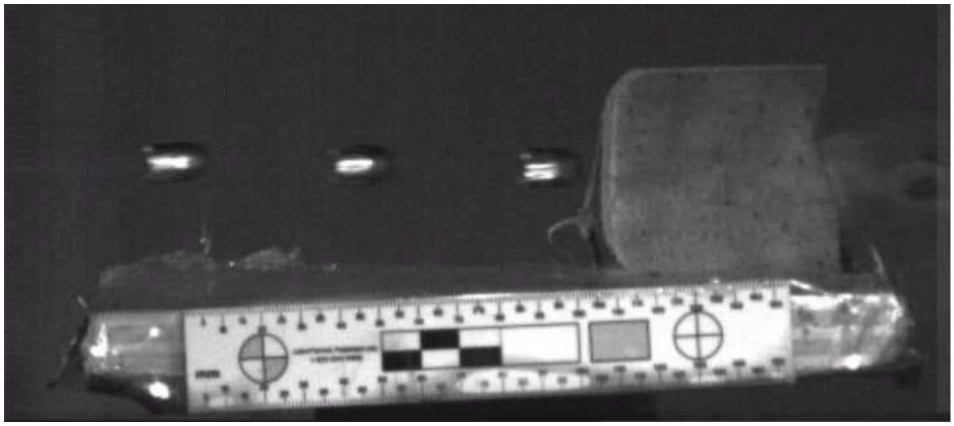

Figure 2: Superimposed time lapse images of a single .45 caliber bullet impacting a blood-soaked sponge, recorded at 10,000 frames per second. The first three bullet images are separated by 0.2 ms; the spatter at far right occurred 0.4 ms later. The black rectangles on the scale bar are 1 cm in length.

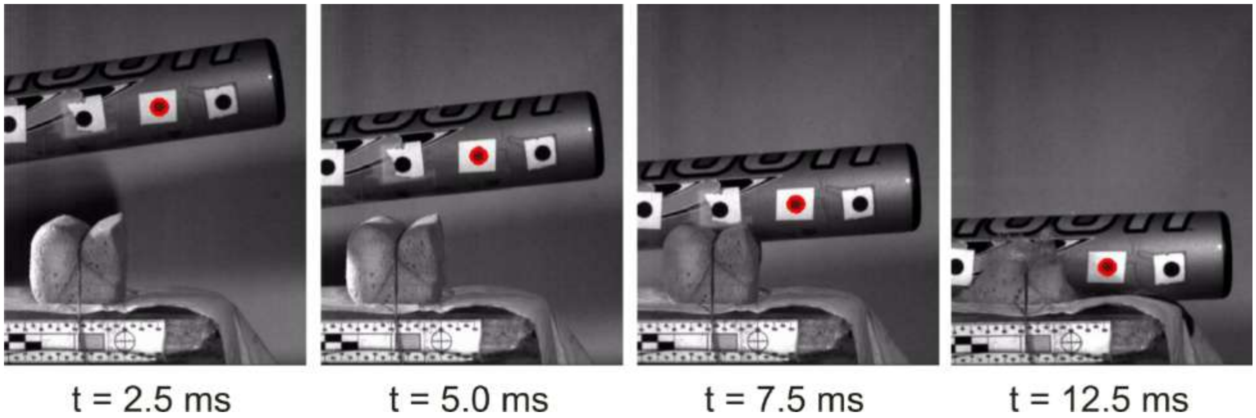

Figure 3: Time lapse images of a baseball bat (diameter = 2.25 in) impacting a blood-soaked sponge, recorded at 10,000 frames per second. A red circle was superimposed during post processing in MATLAB to identify the tracked position of the bat versus time. Black rectangles on the scale bar are 1 cm in length.

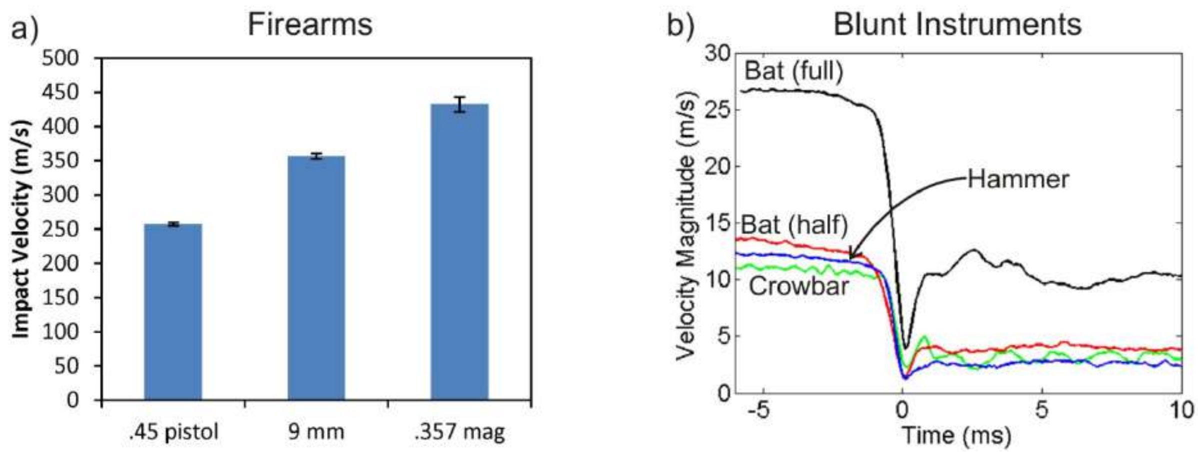

Figure 4: (a) Mean bullet velocities versus type of firearm, as extracted from time lapse images like those shown in Figure 2. Error bars represent one standard deviation. **(b)** Representative velocities of various blunt instruments versus time immediately before and after impact with the blood-soaked sponge.

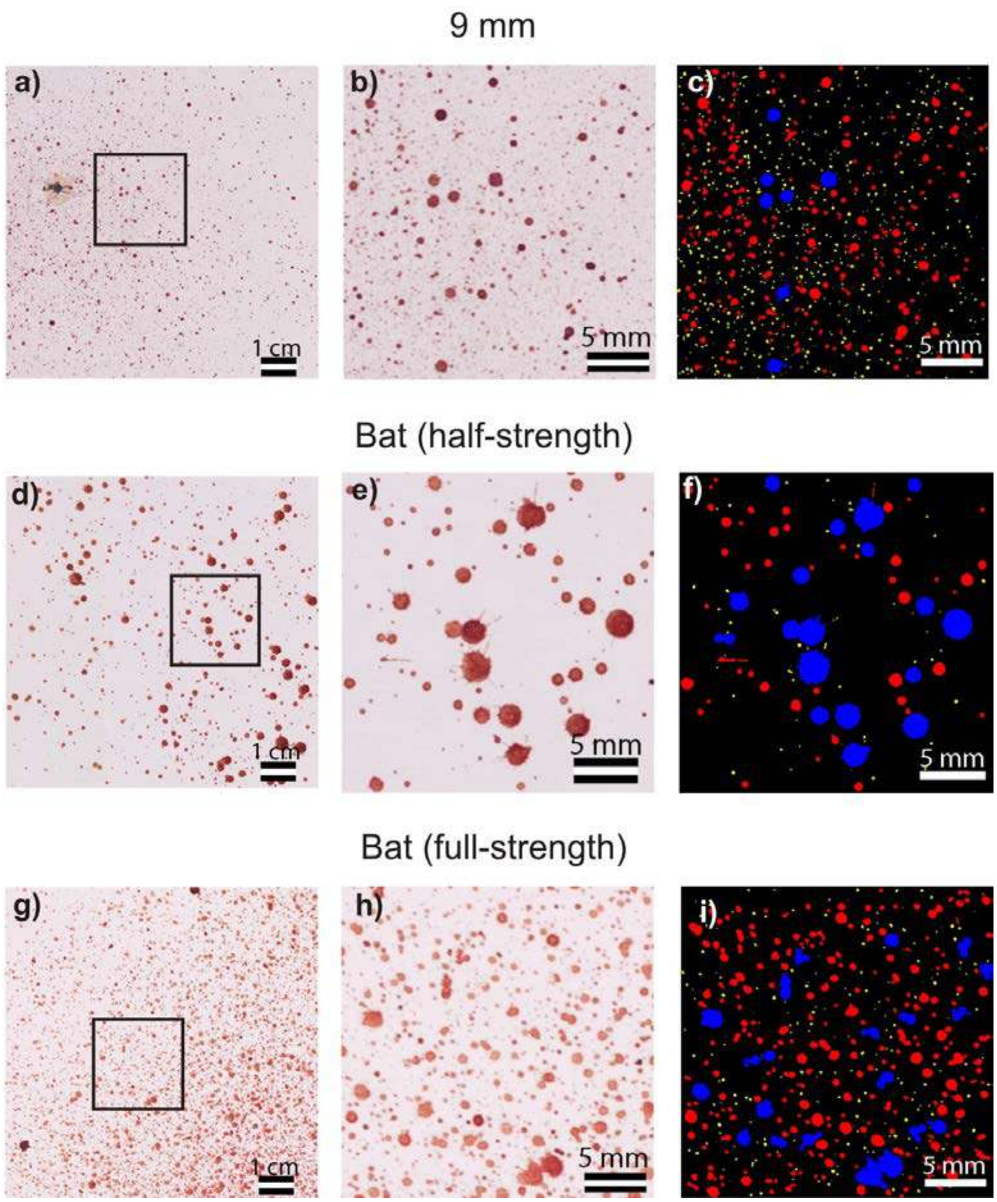

Figure 5: (a) Representative image of a bullet impact spatter pattern, generated by a 9 mm bullet with an impact velocity of 348 m/s. **(b)** True color and **(c)** false color magnification of the box in (a). Colors: blue, $1 < d < 3$ mm, red, $0.27 < d < 1$ mm, yellow, $d < 0.27$ mm. **(d)-(f)** Representative image and magnifications of a spatter pattern generated by a baseball bat swung at half-strength (impact velocity = 10.5 m/s). **(g)-(i)** Representative image and magnification of a spatter pattern generated by a baseball bat swung at full-strength (impact velocity = 25.2 m/s).

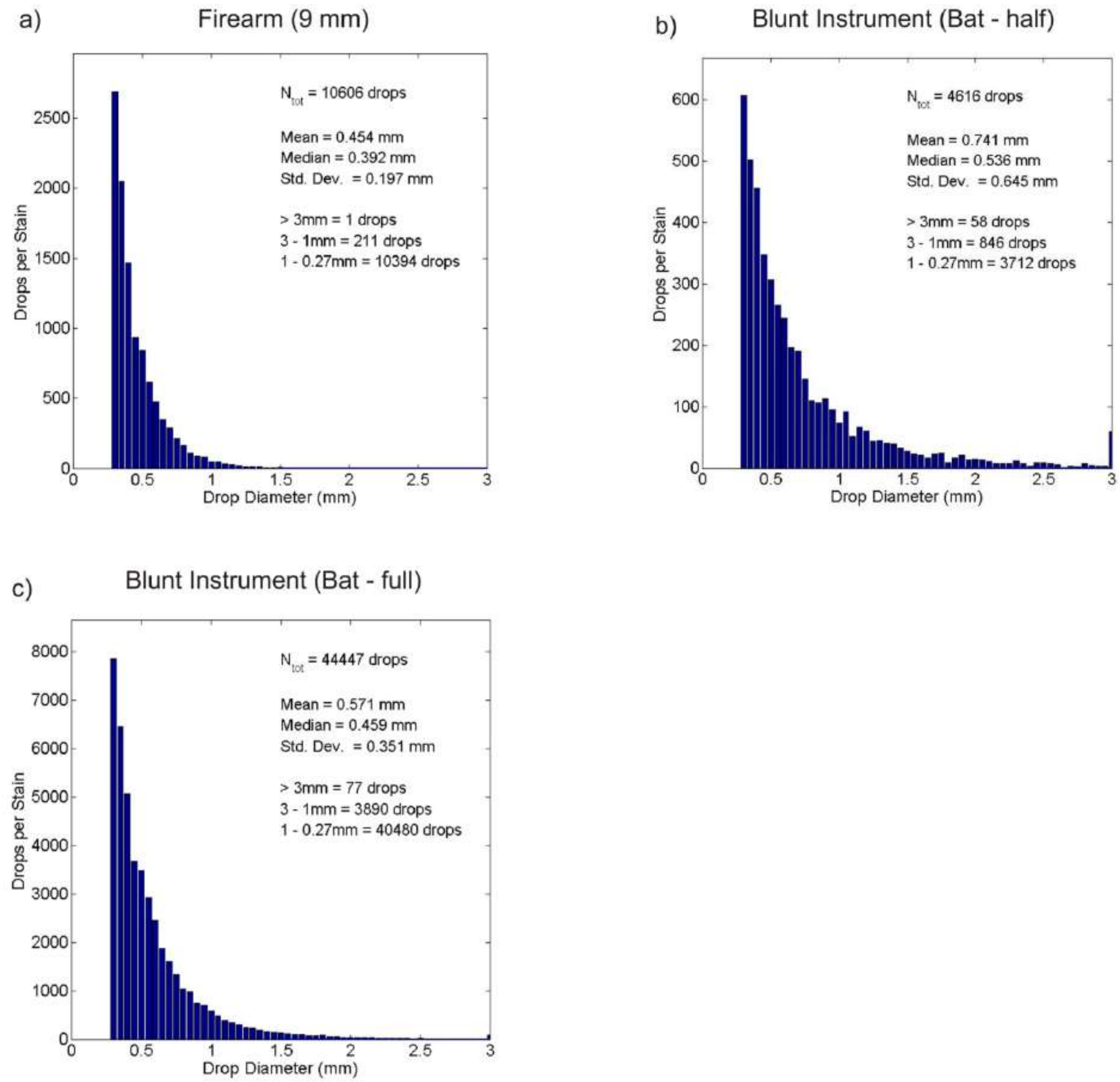

Figure 6: Histograms of the drop size distributions for the spatter patterns shown in Fig. 5: **(a)** 9 mm gunshot, **(b)** bat swung at half-strength, **(c)** bat swung at full-strength.

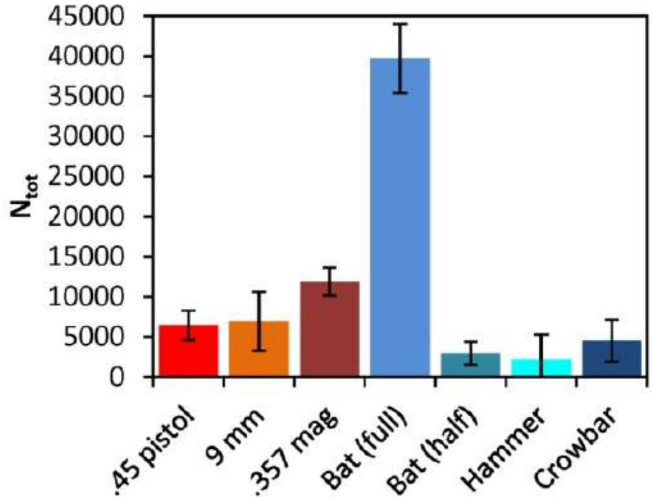

Figure 7: Average cumulative number of drops per spatter pattern versus weapon type, for L = 12 inches. Error bars represent one standard deviation over three trial replicates.

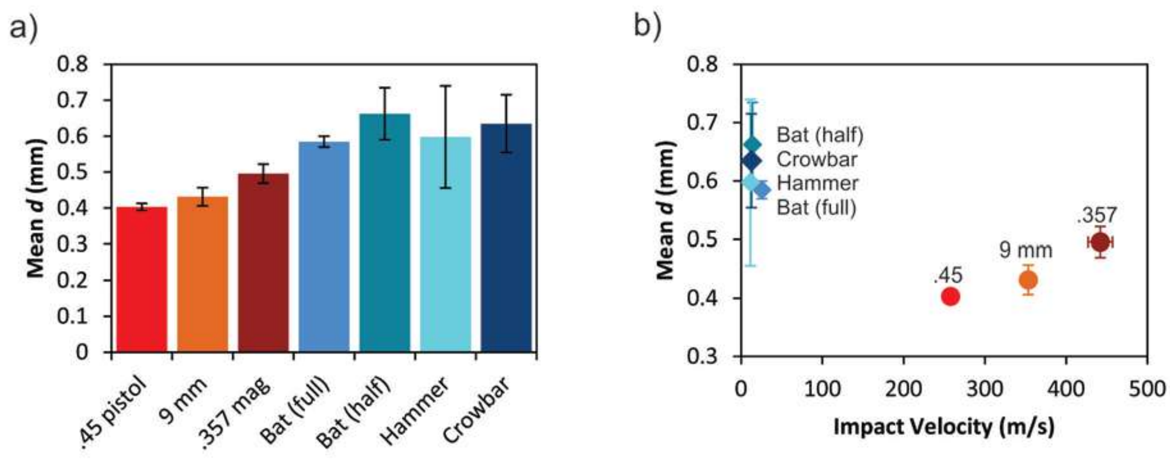

Figure 8: (a) Average drop diameter of all droplets (>0.27 mm) in a spatter pattern versus weapon type, for L = 12 inches. (b) Average drop diameter of all droplets (>0.27 mm) in a spatter pattern versus the weapon impact velocity. All vertical error bars represent one standard deviation over three trial replicates; horizontal error bars in (b) represent one standard deviation in observed impact velocity as extracted from high speed video. Note that the variation in impact velocity for a particular weapon type are negligible compared to the difference in velocity between weapon types.

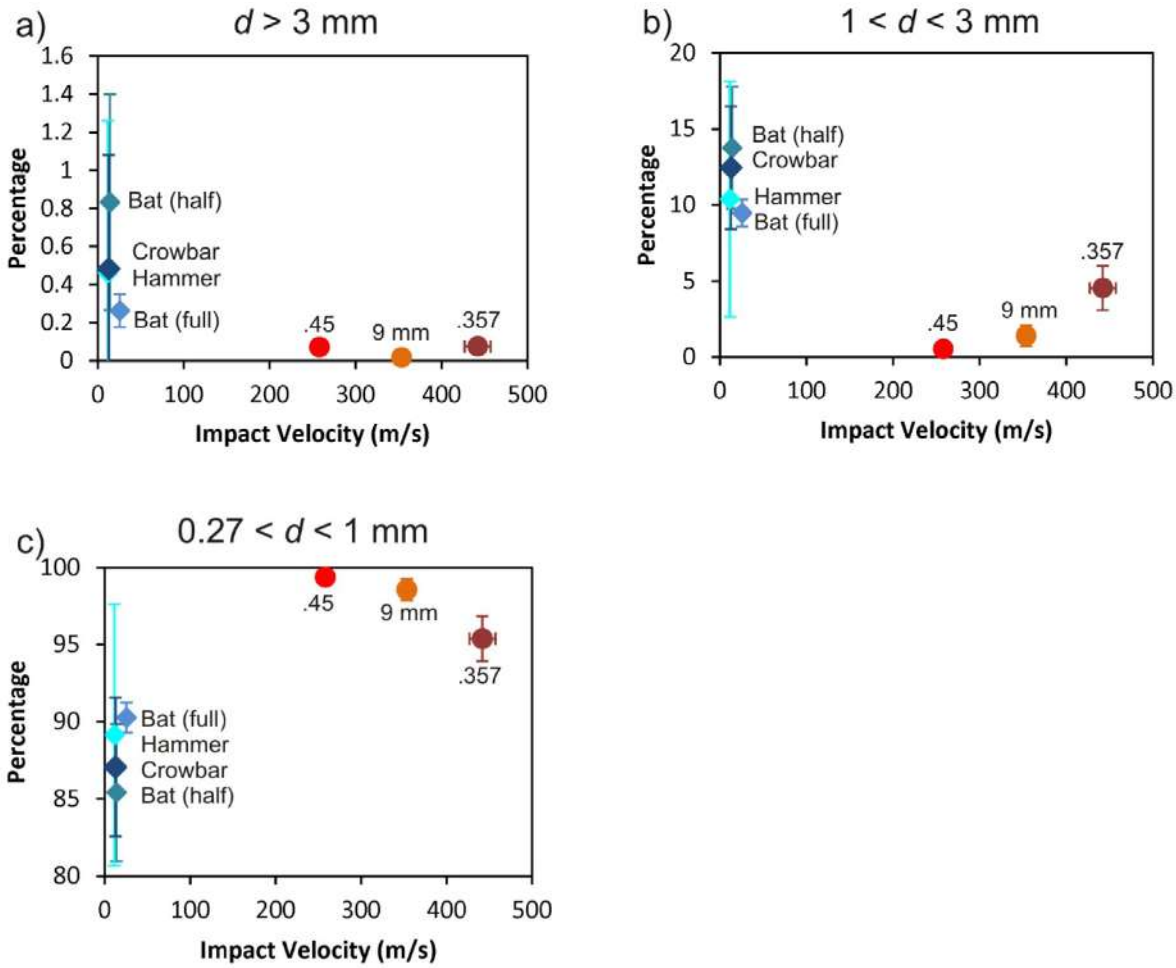

Figure 9: Relative percentages of droplets within different size ranges versus impact velocity, for L = 12 inches. **(a)** Percentage of drops greater than 3 mm in diameter. **(b)** Percentage of drops between 1 and 3 mm in diameter. **(c)** Percentage of drops between 0.27 and 1 mm. Note the three percentages for each weapon type sum to 100. Error bars represent one standard deviation over three trial replicates.

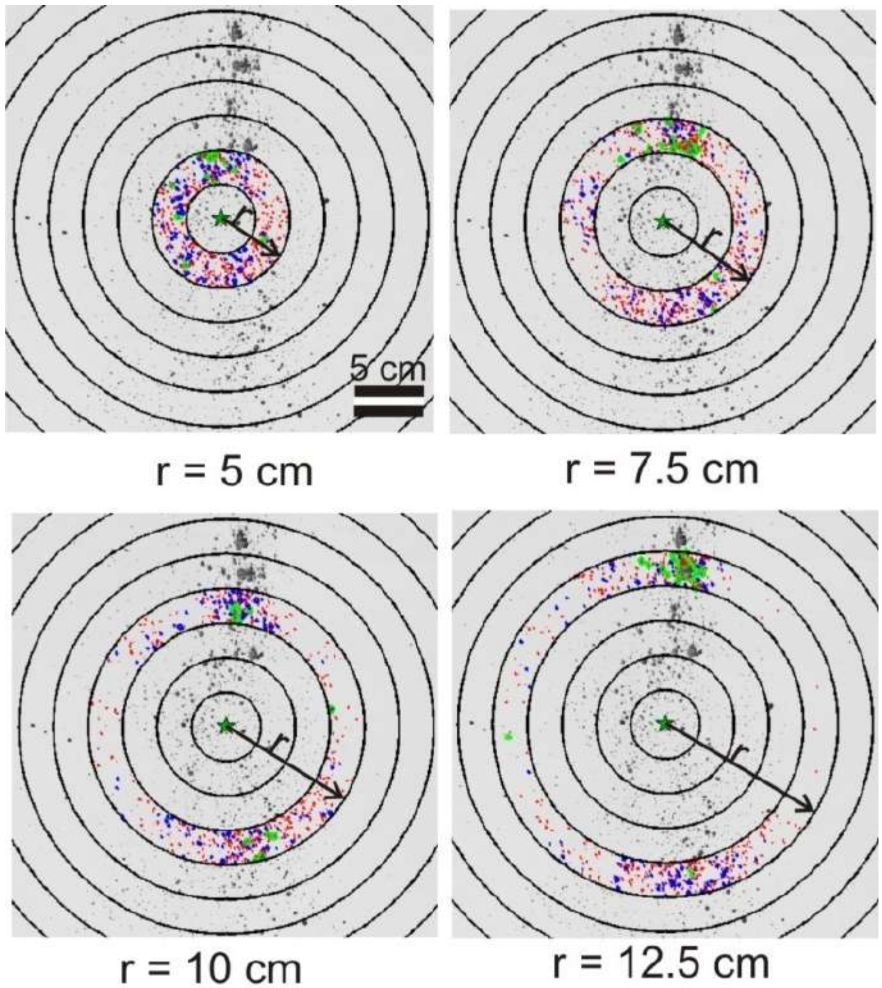

Figure 10: Illustration of quantitative measurements versus position within a representative spatter pattern. Statistics are measured within each annulus at a specified distance from the overall pattern centroid (denoted here with a green star).

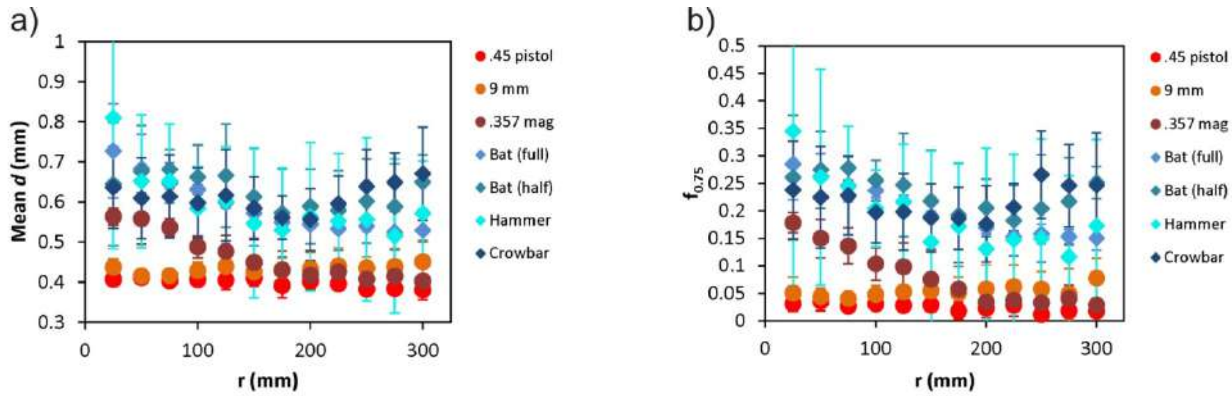

Figure 11: (a) The mean drop size within a 2.5 cm wide annulus as a function of radial position from the overall pattern centroid, for L = 12 inches. **(b)** The fraction of drops larger than 0.75 mm in diameter as a function of radial position from the overall pattern centroid, for L = 12 inches. All error bars represent one standard deviation over three trial replicates.

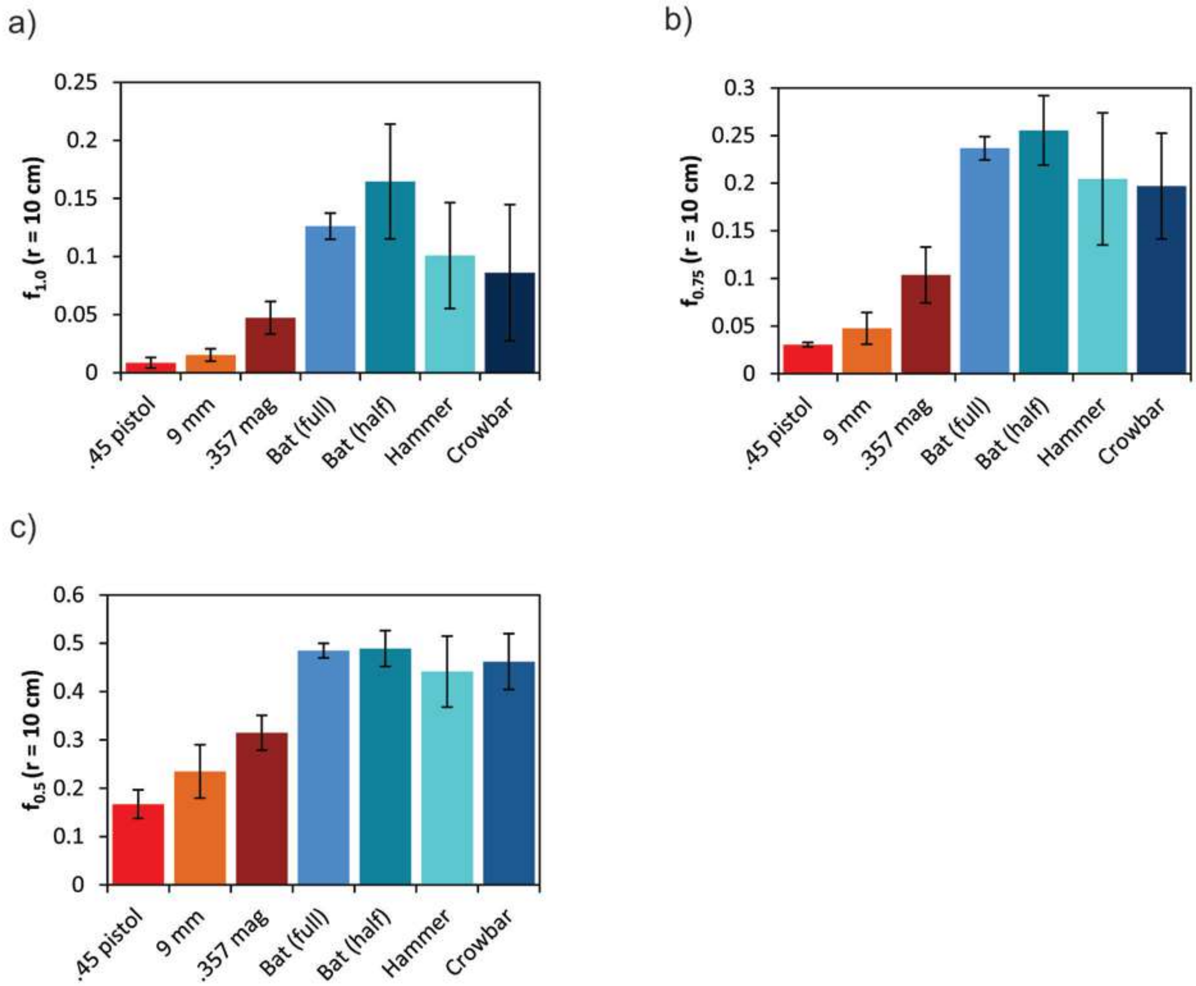

Figure 12: The fraction of drops greater than a threshold diameter within a 2.5 cm annulus located 10 cm away from the pattern centroid. (a) 1.0 mm threshold; (b) 0.75 mm threshold; (c) 0.5 mm threshold. The error bars show the standard deviation over three replicate trials.

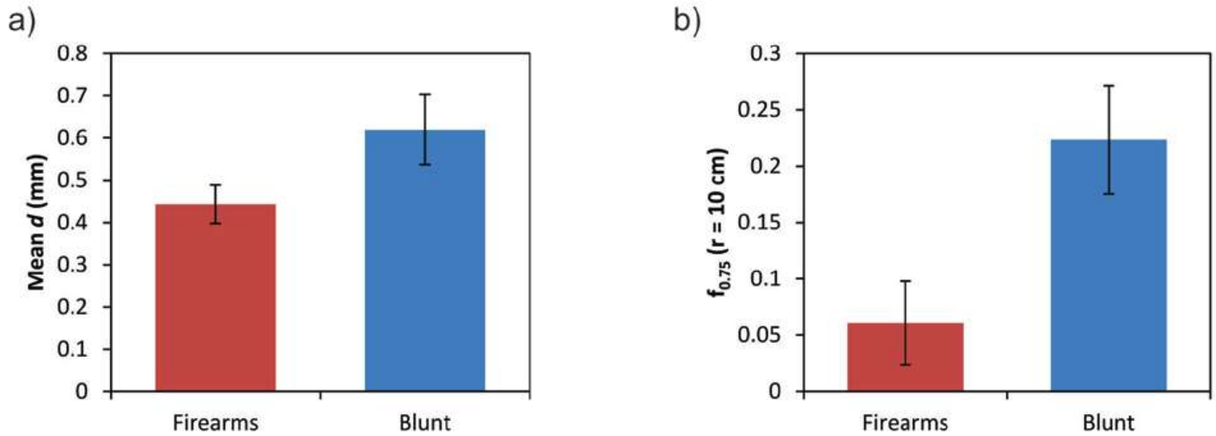

Figure 13: (a) Mean diameter of drop size for the generic weapon types, averaged over all samples. The means differ in a statistically significant sense, with $p = 1.51 \cdot 10^{-5}$. (b) Mean value of $f_{0.75}$ (r = 10 cm) for generic weapon types, averaged over all samples. The means also differ in statistically significant sense, with a $p = 7.91 \cdot 10^{-8}$. All p values calculated using standard ANOVA methodology.

Weapon Type	Mean *d* (mm)	$f_{0.75}$ r = 10 cm
Firearms	0.44	0.06
Blunt	0.62	0.22
Difference	**40%**	**267%**

Table 2: Comparison of the difference in magnitude between mean diameter and $f_{0.75}$, averaged over all firearm types or blunt instrument types.

0.45 vs.	9 mm	.357 mag	bat (full)	bat (half)	hammer	crowbar
mean d	0.144384	0.004622	6.262E-05	0.003517	0.077088	0.007735
$f_{0.75}$ (r = 10 cm)	0.152376	0.012603	8.7202E-06	0.00044	0.012203	0.006572

Table 3: Comparison of the *p* values between the 0.45 caliber spatter patterns and every other weapon type, for both mean diameter and f0.75, as calculated using standard ANOVA methodology.

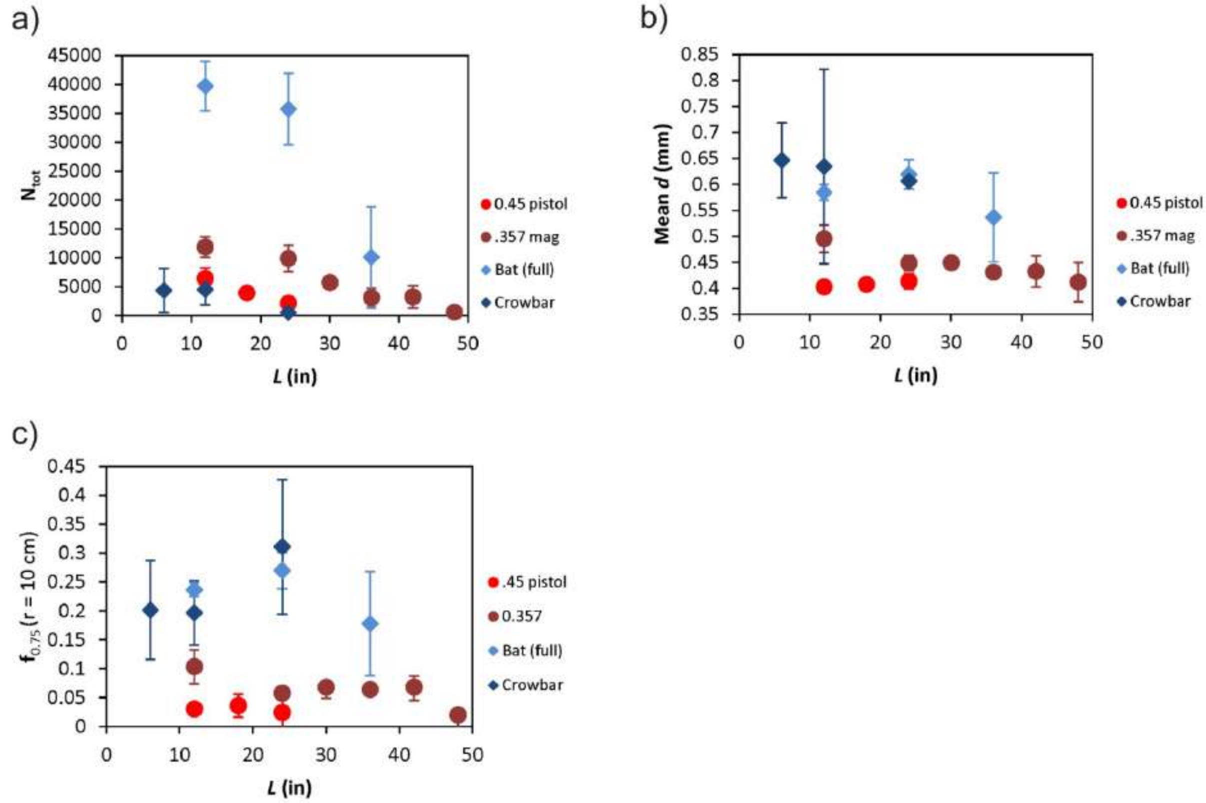

Figure 14: Various pattern statistics as a function of the impact-to-target distance *L*. **(a)** The total number of drops in the spatter pattern. **(b)** The mean diameter of all drops (> 0.27 mm) in the spatter pattern, averaged over three trial replicates. **(c)** The fraction of drops larger than 0.75 mm in an 2.5 cm wide annulus located 10 cm from the overall pattern centroid, averaged over three trial replicates. All error bars represent one standard deviation over three trial replicates.

Part 2: A Double-Blind Investigation of Impact Velocity Assessment for Gunshot and Blunt Instrument Spatter Patterns

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ABSTRACT

Bloodstain Pattern Analysis (BPA) has traditionally involved qualitative characterizations that rely primarily on the visual aspects of a particular stain. Because of this reliance on visual assessment, BPA has been criticized for perceived subjectivity, lack of scientific support, and susceptibility to context bias. One major source of controversy involves the differentiation between so-called "medium velocity" and "high velocity" patterns, the legacy terminology often associated with stains generated by blunt instrument and gunshot impacts respectively. Despite the clear forensic value in assessing the type of impact that generated a particular spatter pattern, the controversy surrounding this differentiation has led most analysts to avoid such assessments. To date, no data or guidelines exist to specify under what conditions medium or high velocity bloodstain patterns can be reliably identified. In this work, we present a double-blind investigation of the error rates associated with identification of impact velocity based on visual assessments of bloodstain patterns. Two cohorts of individuals, ten highly trained BPA analysts and ten forensic science graduate students, both visually assessed the same set of 100 bloodstain patterns created in a controlled environment with known impact velocities and target distances; in this manner, we investigated the accuracy of 2,000 unique bloodstain pattern assessments. We find that the "high velocity" patterns generated by gunshot were identified with high accuracy, yielding an error rate of only 0.21% amongst

the trained BPA analysts. In contrast, the "medium velocity" patterns generated by blunt instrument impacts were much more problematic, yielding analyst error rates as high as 38%. We demonstrate that it is statistically more likely for the blunt instrument spatter patterns to be incorrectly identified as "high velocity" bloodstains when there is a preponderance of small drops located near the pattern's center, thus mimicking one of the key visual cues for a high velocity pattern. Moreover, we find that the respondents had on average a 30% probability of unknowingly changing their assessment when presented with the same medium velocity pattern simply rotated 180 degrees, indicating that the error rates had a significant stochastic aspect. Our findings suggest that great caution should be exercised when assessing the impact velocity for a spatter pattern in the absence of secondary indicia, and highlight the need for more objective criteria for interpreting bloodstain spatter patterns.

INTRODUCTION

The main goal of crime scene reconstruction is to understand and interpret criminal events and their sequence, to help bring justice against those responsible. Bloodstain pattern analysis (BPA) plays a significant role in this process by helping analysts better understand blood-shedding events and by helping establish culpability for criminal acts [1,2]. Considering the potential evidentiary value of BPA, it is clear the framework in which BPA assessments are made should be based on solid scientific methodology and supported by robust statistical data [2]. While some types of bloodstains and their characteristics are well understood, others are less understood [3-7]. The National Research Council (NRC) 2009 report on the state of forensic science bluntly stated: "the opinions of bloodstain pattern analysts are more subjective than scientific" [8].

The topic of blood spatter produced from impact forces with "medium and high velocities" is one of the most controversial issues regarding BPA. Traditionally, a high velocity impact spatter pattern is defined as spatter "associated with force in excess of 100 feet per second" and medium velocity spatter patterns are characterized as "resulting from an impacting force between 25 and 100 feet per second" [9,10]. Despite the widespread use of this terminology for almost 4 decades, the controversy surrounding the differentiation between medium and high velocity impacts led key BPA organizations (e.g., Scientific Working Group on Bloodstain Pattern Analysis [SWGSTAIN]) to recommend against making any type of differentiation. Instead, most analysts have adopted a broader category of "Impact Spatter," which encompasses all "patterns with no linear orientation" and "with radiating distribution," making no reference to impact velocity at all [9].

One key reason for controversy, in addition to the lack of performance studies and the claims of subjectivity, is the possibility that context bias also may inhibit accurate bloodstain pattern assessment. Indeed, the NRC strongly criticized context bias in BPA in their 2009 report, stating, "…many bloodstain pattern analysis cases are prosecution driven or defense driven, with targeted requests that can lead to context bias" [8]. In real criminal investigations there is no way to measure whether context bias has interfered in an analyst's final determination. Although it is unlikely that all analysts' work are tainted by context bias, no representative statistical data exist to assess determinations made outside of criminal investigations.

Considering the highly controversial terminology issue regarding bloodstain patterns in current forensic practice and literature, it is necessary to address the terms selected for use in the following content. The use of the terminology "high velocity spatter pattern" and "medium velocity spatter pattern," originally introduced by Herbert MacDonell in the 1971 [11], has and continues to be controversial [8]. The International Association of Bloodstain Pattern Analysts (IABPA), SWGSTAIN, and many other organizations and practicing analysts currently do not accept *medium* and *high velocity* as adequate descriptors and these categories are shown to be "inappropriate" [12] and "misleading" [13] for classifying impact spatter patterns. "There can be no clear delineations between a stain that constitutes *medium* versus a stain that constitutes *high* velocity" supports the opinions BPA professionals who believe these terms are insufficient [14]. Some publications even describe these terms as problematic and outdated, as evidenced in at least one recent BPA textbook where a new taxonomic system is outlined to replace the "old" classification because "there are several problems associated with the *velocity* method of description, being that velocity's association, nor its foundation, to a specific spatter size has yet to be explained or defined" [9].

Although the terminology is controversial, it is clear that there is still great forensic value in determining whether a particular spatter pattern was induced by a blunt instrument impact or a gunshot. The main goal of this study is to determine under what conditions a bloodstain analyst can accurately assess whether a particular blood spatter pattern was generated by a blunt instrument impact or a gunshot. Toward this end, we conducted a double-blind study where participants were asked to assess bloodstain patterns generated under controlled laboratory conditions. The respondents were provided no information other than the image of the pattern itself, thus preventing context bias. The key finding is that spatter patterns generated by gunshot were identified with high accuracy, but patterns generated by blunt instruments were correctly identified at much lower rates. Our findings provide insight on situations where bloodstain analysts can confidently assess impact velocity, and should serve as a citable resource available to forensic scientists.

STUDY DESIGN AND METHODOLOGY

Generation of the Bloodstain Patterns

The bloodstain patterns to be used in the study were generated under controlled laboratory conditions, as described in detail in our companion paper [15]. Briefly, blood-soaked sponges were impacted either with blunt instruments (e.g., baseball bats) or various caliber bullets. The spatter impacted a white sheet of plotter paper at a specified distance from the sponge. Images of representative spatter patterns generated by a .357 Magnum, a crowbar and a baseball bat are shown in Fig. 1. The blood-shedding simulations were recorded using a high-speed video camera (Phantom v7.3), using a telescopic lens set and frame rates ranging between 10,000-15,000 frames per second. From the video recordings, exact velocities of the impacting objects were calculated. By digitizing the resulting spatter patterns, quantitative statistics were extracted from each pattern, including the total number of drops, mean drop diameter, and drop size distribution. A total of 47 gunshot spatter patterns and 33 blunt instrument spatter patterns were included in the study. A more detailed discussion of the quantitative image analysis is provided in our companion paper [15].

Two other types of bloodstains were also generated to provide some variation in pattern types and serve as controls. First, a small number of patterns (six total) were generated by dripping a specified blood volume onto the paper from a stationary position at varied distances above the target surface. A representative drip pattern is shown in Fig. 2A. The action of the blood dripping into a puddle of blood on the paper also induced some splashing; these patterns are accordingly categorized here as "drip/splash" patterns. Second, a control set of 9 bloodstain patterns were generated by performing a low velocity "finger flicking", i.e., a gloved hand was dipped in blood and then the blood was repeatedly 'flicked' onto the target paper from a distance of approximately 12 inches. As shown in Fig. 2B, this procedure yielded bloodstain patterns with qualitatively similar visual characteristics to spatter patterns generated by blunt instruments and firearms, but which were generated by a process that had nothing to do with a blunt instrument or gunshot impacts. These patterns are strictly considered "cast-off" by the commonly accepted definition [16], although the "hand flicking" manner in which these patterns were produced is not typically encountered in actual crime scenes. These patterns were included here to serve as a control, to gauge how participants would assess non-spatter bloodstain patterns in the absence of any contextual information.

Double-Blind Study Design

A representative set of 95 different bloodstains (47 generated by gunshot, 33 by blunt instrument impact, 9 by hand-flicking and 6 by dripping) were chosen and randomly numbered for inclusion in the study. To ensure that the study was performed in a double-blind fashion, one graduate student helped generate the bloodstain patterns experimentally (as described elsewhere [15]), and then the randomly numbered patterns were handled by another graduate student responsible for administering and compiling the analyst assessments. In our companion study, the original bloodstain patterns were photographed using a high-resolution camera, Canon® EOS 7D digital SLR, fixed with an EF-S 60mm f/2.5 Macro lens. The process of stitching together the images, however, produces slight artifacts in light intensity near the edges of each image, which we judged would be distracting to study participants (cf. Figs 1 and 2). Accordingly, for this study a large-scale, commercial scanner (Océ TDS800 Pro Series) was used to produce full size (1:1) grayscale photocopies with a resolution of 400 dots per inch with direct dot positioning. Because of resolution limitations, our digitally stitched images are shown in Figs. 1 and 2, but we emphasize that the study participants only saw high resolution 1:1 copies without stitching artifacts. Our visual comparison of the original spatter patterns and the high-resolution photocopies confirmed that all droplets visible by the naked eye were faithfully reproduced in the photocopies provided to the study participants.

An additional five bloodstain patterns from the gunshot and blunt instrument spatter patterns were chosen at random, rotated 180 degrees, assigned separate numbers from the originals, and then included in the sample set to yield a total of 100 patterns. The study participants were not informed that the bloodstain patterns included any duplicates. This set of rotated patterns was included as a further control to test for consistency in participant responses.

Each study participant was provided the full-size, grayscale reproductions of all 100 bloodstain patterns, as well as standardized response forms, detailed instructions and definitions, and a questionnaire about their experience and qualifications as a bloodstain analyst. Each participant was asked to carefully study each bloodstain pattern and to assess what type of bloodstain pattern it was. The participants were provided with the following four categories of bloodstain spatter patterns:

"High velocity" A bloodstain pattern resulting from an object impacting a blood source at 100 feet per second or greater. A typical example is spatter resulting from a gunshot.

"Medium velocity"	A bloodstain pattern resulting from an object impacting a blood source at roughly 25 feet per second. A typical example is spatter resulting from the impact of a blunt instrument swung by hand.
"Dripped/splashed "	A bloodstain pattern resulting from the impact either of blood droplets dripping by gravity, or resulting from a volume of blood that falls or spills onto a surface. A typical example is spatter resulting from blood drops dripping into a pool of blood.
"Cast-off"	A bloodstain pattern resulting from blood drops released from an object or limb while in motion. A typical example is spatter resulting from drops being "flung" off a bloody object or weapon such as a crow bar.

We emphasize that in utilizing the above definitions we are not advocating the use of the legacy terminology "medium velocity" or "high velocity" for characterization of spatter patterns, which as discussed previously has been quite controversial. Importantly, our instructions specifically excluded any definitions based on observed mean drop size (e.g., MacDonell's criteria based on number of drops within certain size ranges). Instead, our instructions only referred to the characteristic weapon impact velocity. As such, the high and medium velocity terminology served here as short-hand for gunshot and blunt instrument impact spatter patterns, which are unquestionably induced by impacts with highly disparate velocities. The typical bullet velocities for the calibers used here were around 300 m/s, while the blunt instrument impact velocities were closer to 15 m/s.

The response forms consisted of an answer bank with nine possible responses for participants to choose from. All sample patterns used in the study were made by a single type of event; respondents were instructed to choose only one answer per pattern. Participants were advised that the 100 samples may or may not include examples of all four pattern types to help minimize expectation bias. The 9 possible responses included:

- Definitely high velocity
- Probably high velocity
- Probably medium velocity
- Definitely medium velocity
- Definitely dripped or splashed
- Probably dripped or splashed
- Definitely cast-off
- Probably cast-off
- Insufficient information / impossible to make a determination

To provide some measure of the participants' confidence in each answer, we also asked them to mark whether they believed the stain was "definitely" or "probably" of a particular type. Specifically, we requested that they use the following definitions for their confidence level:

Definitely: You are confident in your assessment about the nature of the impact velocity, and you would be willing to testify about it in court.

Probably: You believe your assessment is most likely correct, but enough doubt remains that you would be unwilling to testify about it in court.

The high velocity spatter patterns were generated by gunshot, so those patterns had an obvious bullet hole that would make assessments trivial. Accordingly, the bullet hole on each pattern produced by gunshot was covered by a 3-cm diameter black circle. Likewise, all other non-gunshot patterns had a 3-cm black circle superimposed somewhere near the center of the stain (cf. Figs. 1 and 2, far right images). To prevent against researcher bias in placing these circles, the exact location was determined by a software algorithm that calculated the centroid of all droplets detected by digital image analysis within the pattern. The location of the black circle was then displaced from the true center by a normally distributed random distance (with standard deviation of 3 cm) and a uniformly distributed random angle. Participants were informed that a black circle was placed in each pattern to either obscure the bullet holes or to mask the lack of a bullet hole, and they were instructed to ignore the black circle to the best of their ability.

We emphasize that no other contextual information about the spatter patterns was provided to the participants. They received no information about the distance from the point of impact to the target surface, nor any other quantitative information regarding the spatter patterns. Likewise, they were not informed about any of the details regarding how the patterns were generated (weapon types, etc.). The instructions provided only the following three pieces of general information: (1) the patterns were generated using pig blood at body temperature, (2) the distance from the impact to the paper target surface ranged from 6 inches to 48 inches, and (3) the patterns were presented to them in random order. The participants were only provided the generic range of distances; no information about the exact distance was provided for any of the patterns. The goal was to determine whether the patterns could be accurately assessed in the absence of any possible contextual bias. The complete set of instructions provided to each participant, including a sample answer form and the questionnaire, are provided in the supplementary material.

Study Participants

Two cohorts of study participants were recruited for the study. The first cohort consisted of 10 qualified BPA analysts with extensive experience in bloodstain pattern analysis. These individuals were required to have a minimum 5 years of experience in forensic science and to have successfully completed at least one recent proficiency test; most of the participants had significantly more experience. These participants were recruited by one of the co-authors (FT), who has extensive ties to the forensic science community; the identities of the participating analysts remained unknown to the other co-authors. A complete set of 100 full-size reproductions of each pattern (as described above) was mailed directly to each participating analyst. In exchange for their time, the analysts received compensation for two days of consulting. They were not required to work consecutively for two days; rather, to prevent fatigue and allow for mailing time, we asked that they complete and return the studies within two months. Included in their mailed packet was a questionnaire so that they could anonymously self-report general statistics such as age, years of forensic experience, approximate number of BPA cases in which they have testified on in court, and their specific bloodstain pattern analysis training history (proficiency testing, education, etc.). The mailing packets were designed to ensure anonymity, with an outer mailing envelope to be opened by FT and an inner sealed envelope containing their confidential pattern assessments and self-response questionnaire; this latter sealed envelope was opened subsequently by the graduate student researcher. In this manner, no set of responses can be traced to any individual participant.

The second cohort consisted of 10 student volunteers from the University of California Davis Forensic Science Graduate Program. These students were required to have no prior experience or training in BPA. Note that this cohort did not serve as a "control" in the traditional medical sense (i.e., where one group receives a placebo); instead, they were included to gauge the effect of experience on assessment accuracy. After selection, the students underwent a brief training course (approximately 3 hours long) to provide them with some rudimentary background in assessment of bloodstain patterns. The training seminar was conducted by Ms. Faye Springer, who gave essentially the same lecture that she has used in blood reconstruction classes or homicide evidence classes that she has taught over the past 30 years. As part of her presentation she showed some of the high speed video produced by Laber, Epstein, and Taylor that is posted on the Midwest Forensic Resource Center website as part of a previous NIJ grant [17]. We emphasize that all of the images in her presentation were from laboratory casework and laboratory experiments prior to this study, i.e., the student cohort was not shown during the training seminar any of the spatter patterns generated experimentally here. In other words, she did not show – nor did she have access to – any of the spatter patterns developed in this particular study. Rather, we strove to provide the students with blood pattern analysis training comparable to what they would receive anywhere in the country. The exact contents of the training presentation are available in the supplementary material.

Training included descriptions of the various types of patterns, typical causes of the different stain pattern types (firearms, blunt instruments, etc.), how to interpret patterns, and how to make identifications using current BPA methodology. Two days after the BPA training was completed, the student participants were asked to assess the same set of 100 bloodstain patterns as the trained analyst cohort, following the same instructions and using the same answer forms. Unlike the analysts, the students were not mailed the study; instead a two-day workshop was held for them to complete their assessments. The student participants were given two days to analyze the 100 bloodstain patterns, under close supervision to prevent collaboration. The full-scale reproductions of the patterns were placed on large tables for their examination. A "no talking" rule was strictly enforced during their assessments. Moreover, they were not permitted to see other participants' responses, and they were not allowed to ask questions or receive help from the study administrators. The student participants did not receive direct compensation but were reimbursed for meal and travel expenses to the workshop. As with the trained analysts, all of the student assessments and questionnaires were submitted without names, so that no set of responses can be traced to any particular participant.

RESULTS

Overall Accuracy and Error Rates

With 20 individual participants, each of whom was asked to assess 100 bloodstain patterns, the double-blind study yielded 2000 unique assessments. The accuracy of these assessments is summarized in Fig. 3, which shows in aggregate form how each cohort assessed the different types of spatter patterns across all 2000 assessments. Note that within Fig. 3 the green shades denote the correct response, the various shades of red and purple denote an incorrect response, while gray denotes the "insufficient information" response. Focusing first on the spatter patterns generated by gunshot (Fig. 3A), we see that the vast majority of the responses correctly indicated high velocity. Within the analyst cohort, 86% of the 480 responses correctly indicated high velocity, while 14% indicated insufficient information. Notably, only 1 of the 480 trained analyst responses incorrectly specified medium velocity, which corresponds to a 0.21% error rate. (This one response is too small a fraction to be observable within the pie chart in Fig. 3A.) The student cohort performed similarly well for the gunshot spatter patterns: 93% of the responses correctly indicated high velocity. However, the student error rate was also higher, with 4.4% incorrectly assessed as medium velocity. Only 2% of the student responses for gunshot spatter patterns were given as insufficient information. Notably, both the trained analysts and the students were very confident of their assessments on the gunshot spatter patterns. The majority of correct high velocity responses were described as "definitely" high velocity, at 67% and 73% of total responses for the analysts and students respectively.

In contrast, the accuracy rates for the spatter patterns generated by blunt instrument impacts were much lower (Fig. 3B). Only 41% of the 370 analyst assessments correctly indicated medium velocity; 38% incorrectly indicated high velocity, cast-off or dripped, while 21% indicated insufficient information. Of the incorrect assessments, the majority of responses indicated high velocity. The students actually performed better on the blunt instrument patterns: 61% of the 370 student assessments correctly indicated medium velocity, while 34% incorrectly indicated high velocity, cast-off or dripped and only 5% indicated insufficient information. The general trends in assessment confidence were also markedly different for the blunt instrument patterns when compared to the gunshot patterns. Only 15% of the analyst responses indicated "definitely" medium velocity, which is almost equaled by the 11% of responses which were incorrectly listed as "definitely" high velocity. The students were more confident in their assessment, with a full third indicating "definitely" medium velocity.

The assessments of the finger-flicked bloodstain patterns are shown in Fig. 3C. Recall that these patterns were included as a control, to see how participants would assess bloodstain patterns that had not been generated by gunshot or blunt instrument impacts but looked qualitatively similar to a spatter pattern. Since the finger-flicking motion technically fits the definition of cast-off, we treated cast-off as the "correct" assessment for this category of bloodstain pattern. Of the 90 analyst responses, only 17% indicated cast-off; 62% of the responses indicated either medium velocity or dripped/splashed, with 21% assessed as insufficient information. Notably, almost a quarter of the analyst responses indicated "definitely" medium velocity. The student responses were qualitatively similar, with only 4% of the 90 responses indicating cast-off, and 96% indicating either medium velocity or dripped. Again, many of the student responses (21%) indicated "definitely" medium velocity. In contrast to the analysts, however, a much higher fraction of the student responses (58%) indicated dripped/splashed. Another notable feature is that none of the 180 combined responses indicated high velocity, suggesting that patterns generated by this type of flicking motion are not readily confused with a gunshot spatter pattern.

The assessments for the final category of bloodstain patterns, those generated by dripping blood, are shown in Fig. 3D. These patterns were assessed with extremely high accuracy. Of the 60 analyst responses, all 60 were "definitely" dripped/splashed. In other words, the error rate was 0%, and the analysts all had high confidence in their (correct) assessments. The students also performed well, with 85% indicating "definitely" dripped/splashed, and an error rate of 10%. All of the incorrect student responses on the dripped patterns were listed as medium velocity.

Correlations with Impact Velocity and Pattern Statistics

The above discussion focused on the aggregate accuracy and error rates, i.e., with respect to all 2000 unique assessments. Within each category of pattern type, however, were patterns created by a variety of weapon types and at different impact-to-target distances. Accordingly, we examined whether particular weapon types or distances were accurately assessed at different rates. To visualize trends in accuracy, we calculated a "weighted score" for each of the 100 individual bloodstain patterns. The weighted score penalized incorrect responses and explicitly accounted for the respondent's confidence level, using the following scheme:

"Definitely" & correct = + 1.0

"Probably" & correct = + 0.5

"Insufficient information" = 0

"Probably" & incorrect = – 0.5

"Definitely" & incorrect = – 1.0

We emphasize that many other scoring schemes could be implemented; we chose this one because it incorporates both accuracy and confidence level in a symmetric fashion. Note that with 10 participant responses per bloodstain pattern, the maximum possible score for a pattern is +10 (if all 10 participants indicated "definitely" the correct response), and the minimum possible score is –10 (if all 10 participants indicated "definitely" the incorrect response). With 2 cohorts, each pattern received 2 weighted scores.

The weighted scores for the gunshot and blunt instrument spatter patterns are plotted as a function of impact velocity in Fig. 4A. Two key trends are apparent. First, all of the gunshot spatter patterns created with velocity bullet impacts (.357 Magnum, .45 ACP, and 9mm Luger) received high weighted scores. The majority of weighted scores were clustered between +7 and +10, with the lowest observed score at +4. This trend is consistent with the aggregate response rates shown in Fig. 3A, which show that most of the gunshot patterns were correctly identified. Fig. 4A indicates, however, that no particular firearm was disproportionately responsible for the small number of incorrect responses.

In contrast, the second key trend in Fig. 4A is that the blunt instrument patterns received a much wider range of weighted scores. The maximum observed score was +9.5, but the minimum score was –7, reflecting the large number of patterns incorrectly assessed with high confidence. Strikingly, of the 74 blunt instrument scores (37 patterns with 2 cohorts), a full third of them (25) received negative weighted scores, indicating that on average the participants had great difficulty in accurately assessing those patterns. Unlike the firearms, however, we see that certain blunt instrument types were more problematic than others. Notably, the majority (22) of the patterns generated with the crowbar received positive scores, while only 3 received weakly negative scores. Contrariwise, the patterns generated with the hammer received primarily negative scores: only 3 positive, and 9 negative.

Patterns generated by the bat were more uniformly distributed between positive and negative weighted scores (12 negative, 25 positive).

Given the trends in Fig. 3B and Fig. 4A, an obvious question is as follows: why were the blunt instrument patterns assessed more poorly than the gunshot patterns? One hypothesis is that the individual participant's accuracy increased with their overall amount of experience or training. We tested this hypothesis by examining the analysts' self-reported statistics regarding years of experience, number of classes and/or certifications, and number of cases worked. We found no statistically significant correlations between amount of experience and assessment accuracy (Fig. 5). This is perhaps not surprising, since the student cohort (all of whom had only a single 3-hour training course) arguably performed as well as the highly experienced analyst cohort.

Another possible explanation is that the patterns themselves contained visual cues that misled the participants. One particularly important parameter is the distance from the impact site to the target surface, which affects the number and size distribution of droplets that actually reach the target surface. We tested the hypothesis that this distance had a corresponding effect on the participant assessments. (Recall that the participants were not informed of the exact distance.) The blunt instrument weighted scores in Fig. 4A are replotted versus impact-to-target distance in Fig. 4B. Although there is some scatter, a general trend is clearly apparent: the vast majority of the negative scores occurred in patterns generated at close distances, i.e., 12 inches or less.

It is well known that the smaller a drop is, the smaller a distance it can travel before aerodynamic drag appreciably inhibits its velocity [18]. In other words, if the target surface is located further away, the fraction of small droplets reaching the surface will decrease. We sought to determine whether this physical phenomenon was affecting the participants' assessments of the patterns, by seeing whether statistics about the droplet sizes were correlated with the weighted scores. In our companion paper, we used digital image analysis techniques to extract the mean size and percentage of small drops. Focusing on the patterns generated by blunt instruments at close distances (6 or 12 inches), we indeed find a statistically significant correlation between mean drop size and weighted score (Fig. 6A). In other words, patterns with smaller mean drop diameters received lower scores, while patterns with larger mean drop diameters received higher scores. A correlation test yielded a p value of 0.0021, indicating a high correlation between mean size and weighted score. Likewise, we observe a strong correlation between percentage of drops less than 1 mm in diameter and weighted score (Fig. 6B), with $p = 0.0104$. For these blunt instrument patterns the participants tended to incorrectly assess them as high velocity (cf. Fig. 3B) if they had a high fraction of smaller droplets. Our tests of other quantitative metrics extracted from the digital image analysis (such as the total number of droplets, or fraction of droplets larger than 3 mm) did not yield any statistically significant correlations ($p < 0.025$). These results strongly suggest that the participants were misled primarily by the presence of a high fraction of small droplets.

Consistency in Assessments

A key advantage of our study design is that we were able to directly test for consistency (i.e., reproducibility) in participant responses for the same pattern. Five patterns were chosen randomly, yielding a set of 4 blunt instrument patterns and 1 gunshot pattern. The patterns were rotated 180 degrees and provided a new random number; a representative example of this rotation procedure is shown in Fig. 7. The participants were not informed that any duplicate patterns were inserted. None of the 20 participants commented in their "notes" section of their answer forms that they noticed the duplicate patterns; the rotation makes the duplication difficult to detect.

The consistency rates for these 5 duplicated patterns are tabulated in Fig. 8 for both cohorts. Note that each row corresponds to a particular pattern (denoted at left), while each column corresponds to a particular participant. The colors indicate the degree of consistency. Green indicates the same assessment was given on both duplicates (i.e., the assessment was consistent). Yellow indicates a change in confidence (from "probably" to "definitely", or vice versa) but that the same category of event (e.g., medium or high velocity) was given. Red indicates that the participant changed his/her assessment from one category to another between the duplicate patterns (i.e., inconsistent assessments were provided). The numbers at the bottom of each column or far right of each row represent the "consistency percentage," which was calculated as the percentage of responses that were consistent in category type if not confidence level (i.e., the percentage of green or yellow boxes in that row or column).

Several trends are apparent. Focusing first on the student cohort (Fig. 8A), we note that only 1 of the ten students was perfectly consistent in his/her assessments; the rest all switched their assessments on at least some of the patterns. Notably, none of the students switched their assessment on the one gunshot pattern duplicate (the .357 Magnum, bottom row), although half of them shifted their confidence level. Two of the patterns, the baseball bat and hammer, were particularly problematic for the students: the consistency rate was only 50% for each pattern.

Similar consistency trends were observed amongst the analyst cohort. Again, only one analyst (participant #17) was perfectly consistent for all five duplicated patterns, but two others (#13 and #20) only shifted some of their confidence levels. Likewise, none of the analysts altered their assessment of the gunshot pattern; only one analyst shifted their confidence of this pattern. The most problematic pattern for the analysts was the pattern generated by crowbar at 12", of which four of the analysts switched their assessment. The patterns generated by hammer at 12" and crowbar at 24" were also problematic, with three of the analysts switching their assessment on each.

It is worth emphasizing that both the student and analysts cohorts had 100% consistency in their assessments of the one duplicated gunshot spatter pattern. In contrast, both cohorts were much less consistent for the duplicated blunt instrument spatter patterns. Of the 80 unique opportunities for the participants to provide a consistent response on the blunt instrument patterns (i.e., 4 patterns and 20 participants), an inconsistent assessment was provided 24 times. In other words, on average the participants failed to give the same assessment on the same pattern 30% of the time. This finding strongly suggests that the assessments of the blunt instrument spatter patterns had a pronounced stochastic aspect.

DISCUSSION

The results of our double-blind study have several implications for the forensic science community. First, our results suggest that bloodstain pattern analysts are unlikely to incorrectly identify gunshot spatter patterns. The error rate for the trained analyst cohort was only 0.2%, with two thirds of the 480 responses indicating high confidence in their (correct) assessments. Likewise, bloodstain pattern analysts are unlikely to misidentify a drip pattern: although the sample size was smaller (N=60), the error rate of the trained analysts was 0%, with 100% indicating high confidence in their assessment.

In contrast, the second main implication is that bloodstain patterns generated by a blunt instrument impact are much more difficult to accurately identify. More than a third of the blunt instrument pattern assessments (N=370) were incorrect, with the majority of those misidentified as high velocity spatter patterns. In other words, many of the spatter patterns generated by impacting a blunt instrument by hand appeared instead to the analysts to have been generated by gunshot. Our quantitative analysis of the drop size distributions indicates that there is a statistically significant correlation between lower mean drop sizes and higher error rates; meaning, patterns with lots of small drops (<1 mm) tended to be incorrectly assessed.

These two main results help clarify the nature of the controversy surrounding impact velocity assessment for spatter patterns: the key problem is that, for small impact-to-target distances, blunt instrument impacts can yield patterns that look like high velocity spatter patterns.

Another significant, and perhaps counterintuitive, result from our study is that we observed no statistically significant correlation between increased experience and accuracy rate. Indeed, minimally trained students arguably performed as well as analysts with decades of cumulative experience. However, the analysts tended to give a significantly higher fraction of "insufficient information" responses, perhaps indicative of a more conservative outlook on pattern interpretation. The immense evidentiary value attached to BPA determinations in real criminal blood-shedding events probably drives this conservatism; the students presumably are less willing to admit "I don't know" even when faced with insufficient information.

Our results suggest two other potentially worrisome aspects for bloodstain pattern interpretation. First, our control patterns generated by "finger flicking" were identified as medium velocity spatter patterns in more than a third of the assessments (N=90). This result implies that a pattern generated simply by shaking blood off of a hand at a crime scene could be incorrectly interpreted as having resulted from a blunt instrument impact. At the same time, however, our results also suggest that it would be very unlikely for an analyst to incorrectly interpret the same pattern as having resulted from a gunshot.

Perhaps a more problematic aspect, however, is the high rate of inconsistent assessments provided by the participants when presented with the same bloodstain pattern twice. For the blunt instrument impacts, on average the participants failed to give the same assessment on the same pattern 30% of the time. This result does not give great confidence in the ability of even highly experienced analysts to reproducibly assess spatter patterns generated by blunt instrument impact. Indeed, the high rate of inconsistency appears to corroborate one of the central criticisms of the NRC report, which was that "the opinions of bloodstain pattern analysts are more subjective than scientific" [8].

We should emphasize, however, that the study was designed to force the respondents to assess the patterns in the absence of any contextual information. This methodology prevented the possibility of context bias: the participants had to assess the patterns based solely on their visual appearance. Thus, in one sense it is impressive that the participants exhibited such extremely high accuracy rates on patterns generated by gunshot or by dripping. Despite the low error rate on gunshot spatter patterns, the much higher error rate on patterns generated by blunt instrument impact suggests that an analyst faced with a spatter pattern of unknown origin might, in the absence of contextual information, incorrectly assess the spatter pattern as having resulted from a gunshot or other high velocity impact.

CONCLUSIONS

Our study leads to two key recommendations. First, bloodstain pattern analysts should indeed be cautious in attributing an impact velocity to a spatter pattern of unknown origin, especially in the absence of secondary indicia (such as bullet casings or bloody blunt instruments found at the crime scene). In situations where such contextual information is unavailable, analysts should be aware of the key asymmetry revealed by our study: spatter patterns generated by gunshot are readily identifiable, but spatter patterns generated by blunt instrument impact, especially at small distances, can also look like a gunshot spatter pattern.

The high rate of inconsistency corroborates the notion that bloodstain interpretation based solely on visual examination is subjective and prone to irreproducibility. The second key recommendation is that bloodstain analysis community would benefit from continued development of objective and quantitative methodologies for assessment of spatter patterns [15].

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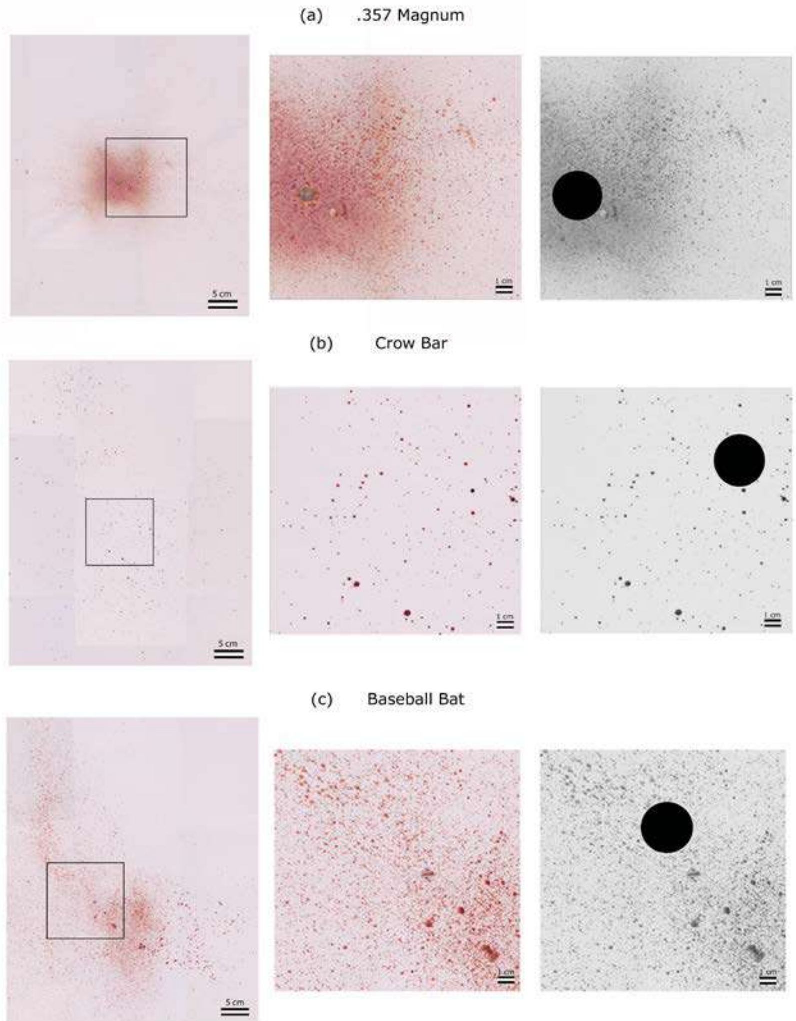

Figure 1: Digital images of representative spatter patterns generated by **(a)** gunshot from a .357 magnum, **(b)** impact with a crowbar, and **(c)** impact with a baseball bat. On the far left is a low magnification image; in the center and right are higher magnification images of the region denoted by the black square at left. The center image shows the original color image, while the image at right shows the grayscale image as seen by the study participants. A 3-cm black circle was superimposed on the grayscale photocopies to obscure either the presence or lack of a bullet hole. Note that the low magnification images at left are composed of several high-resolution photographs stitched together to create one large image; the study participants, however, were provided full-size (1:1) grayscale scans that lacked stitching artifacts.

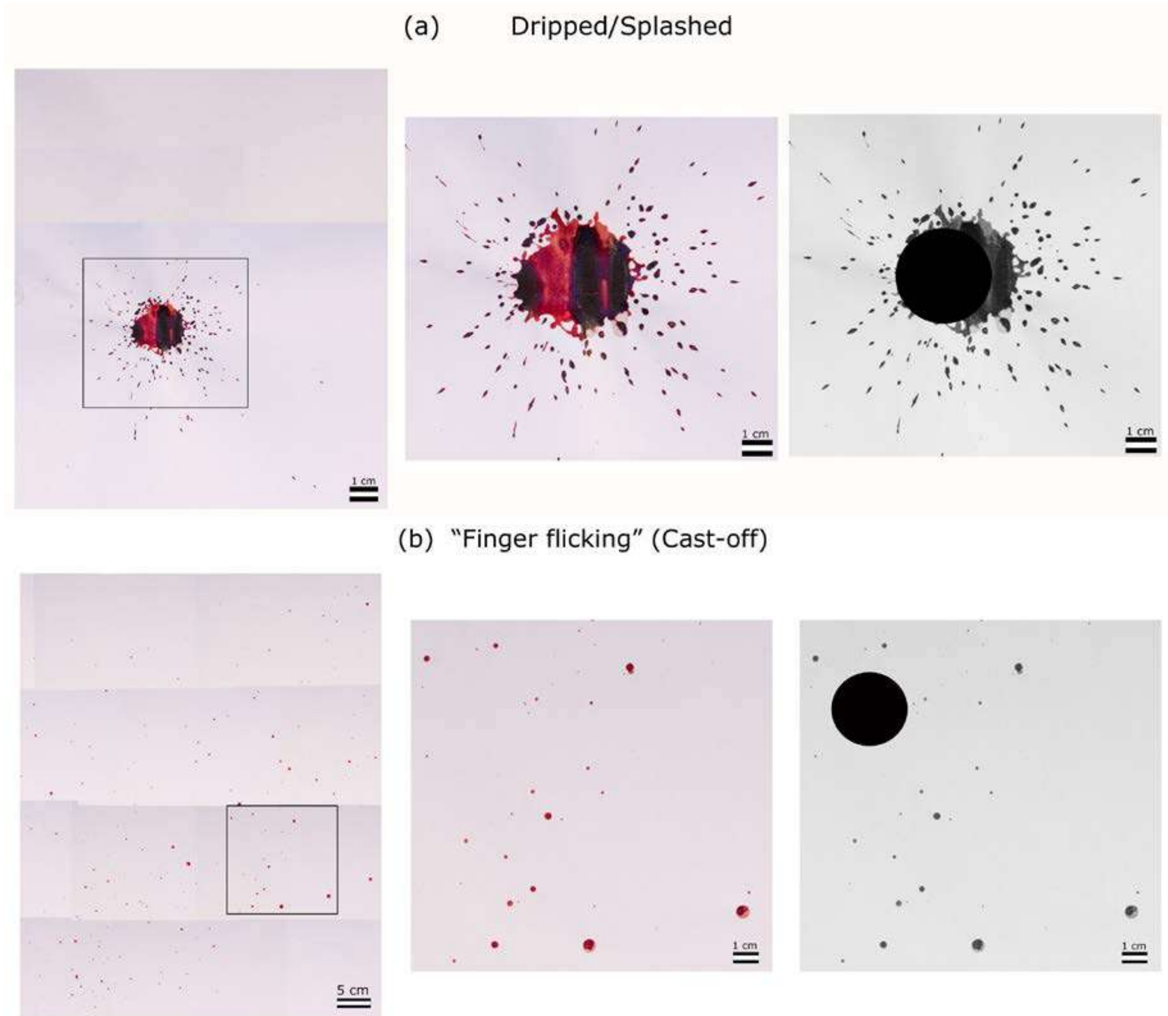

Figure 2: Digital images of representative spatter patterns generated by **(a)** dripping blood from a height of 42 inches, and **(b)** by "flicking" blood-soaked fingers at the paper. Other details same as in Fig. 1.

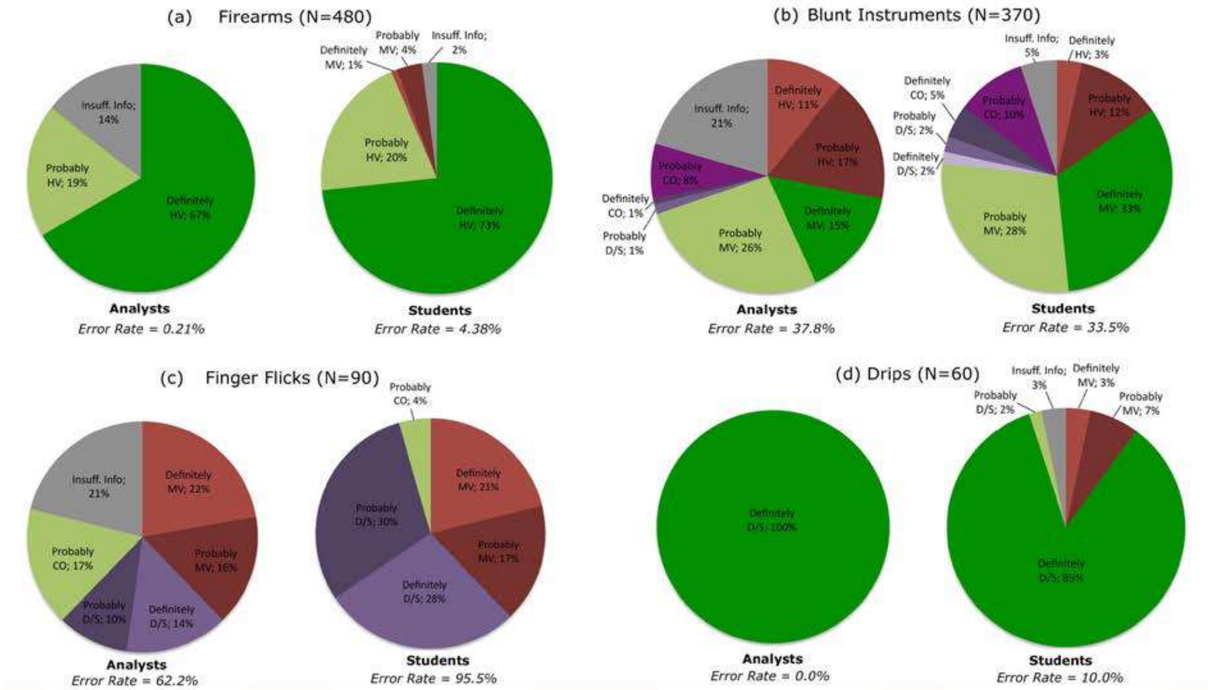

Figure 3: Pie charts denoting the aggregate assessments of each spatter pattern, organized by type of bloodstain pattern and cohort. In each chart, green shades denote the correct assessment, red and purple shades denote an incorrect assessment, and grey indicates an "insufficient information" assessment. Aggregate error rates, calculated based on the number of incorrect assessments (excluding insufficient information) are reported under each respective pie chart. Acronyms: HV = high velocity; MV = medium velocity; CO = cast-off; D/S = dripped/splashed. The number of unique assessments provided by each cohort is denoted as N. **(a)** Bloodstains generated by various caliber firearms. **(b)** Bloodstains generated by various blunt instrument impacts. **(c)** Bloodstains generated by low velocity "finger flicking". **(d)** Bloodstains generated by dripping into a puddle of blood.

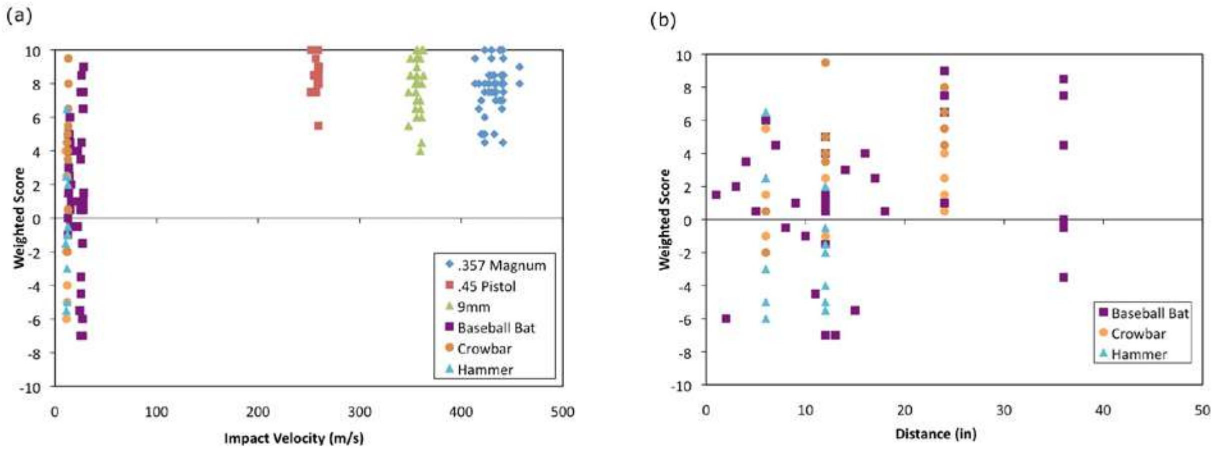

Figure 4: (a) Weighted scores for the firearm and blunt instrument spatter patterns, from both cohorts, versus the impact velocity as measured by high speed video, cf. reference [15]. **(b)** The same weighted scores for just the blunt instrument spatter patterns, plotted instead as versus the distance between the point of impact and the target paper.

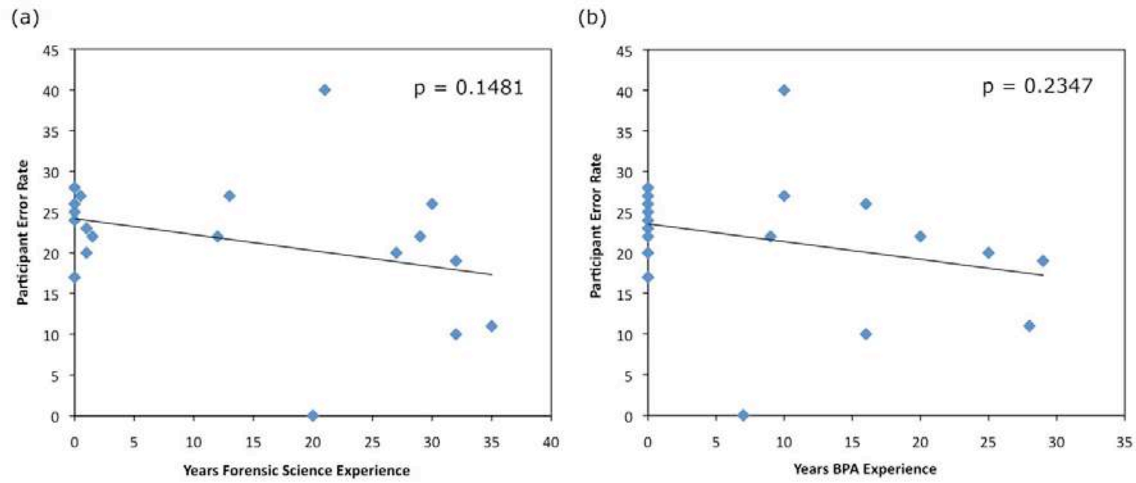

Figure 5: **(a)** Error rates for all 20 study participants (analysts and students combined) versus years of forensic science experience (self reported). **(b)** The same error rates instead versus total years of BPA experience (self reported). Both sets of data failed to reject the null hypothesis of no linear correlation using $p \leq 0.05$ as the threshold for statistical significance.

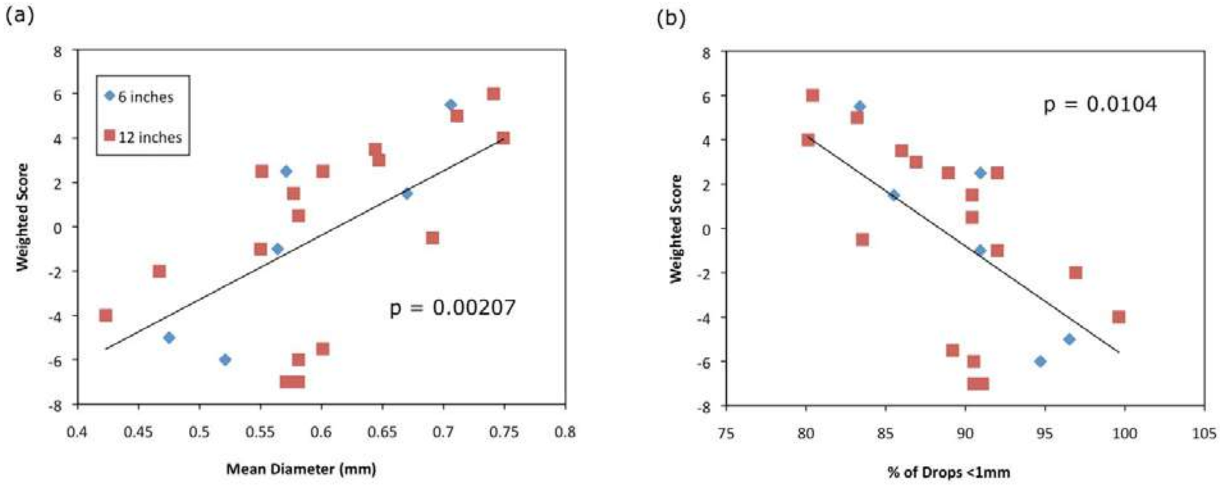

Figure 6: (a) Weighted scores for all blunt instrument spatter patterns generated at distances of 6 or 12 inches versus the mean size droplet size within each pattern **(b)** The same weighted scores plotted instead versus the percentage of drops smaller than 1 mm within each pattern. The drop size statistics were extracted by quantitative image analysis, cf. reference [15].

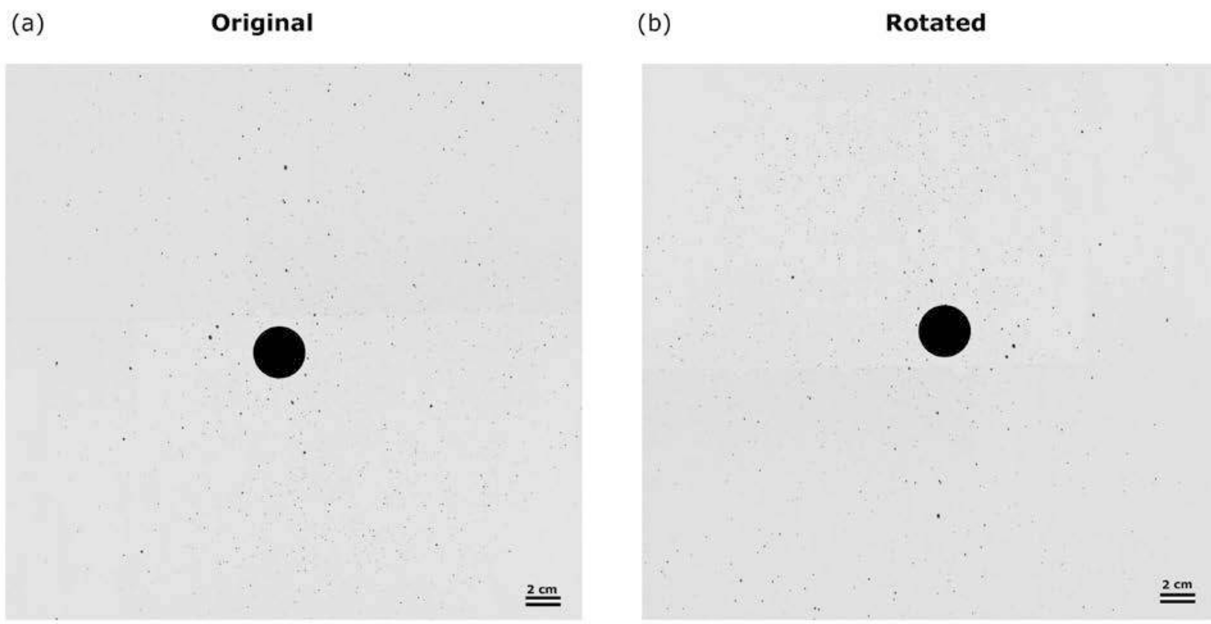

Figure 7: Representative images of a spatter pattern generated by a crowbar impact in **(a)** its original orientation and **(b)** after rotation by 180 degrees.

(b) **Students**

Participant #	1	2	3	4	5	6	7	8	9	10	Consistency (%):
Crow Bar 24"				Prob MV → Def MV		Def MV → Prob MV	Prob HV → Prob CO	Prob MV → Def MV	Prob MV → Def MV		90
Baseball Bat 12"			Prob HV → Def MV		Prob HV → Prob MV		Insuff Info → Prob MV	Prob MV → Def CO	Prob HV → Prob MV		50
Hammer 12"		Def CO → Def MV		Def MV → Prob CO		Prob CO → Def MV	Prob MV → Insuff Info		Prob CO → Def CO	Prob CO → Def MV	50
Crow Bar 12"		Def MV → Prob HV	Def MV → Prob MV		Prob MV → Def MV				Prob HV → Def MV	Def MV → Prob MV	80
.357 Magnum 12"		Def HV → Prob HV	Def HV → Prob HV	Prob HV → Def HV	Def MV → Prob MV				Prob HV → Def HV		100
Consistency (%):	100	60	80	80	80	80	40	80	60	80	

(c) **Analysts**

Participant #	11	12	13	14	15	16	17	18	19	20	Consistency (%):
Crow Bar 24"	Prob HV → Prob MV	Prob MV → Def HV				Prob MV → Insuff Info					70
Baseball Bat 12"			Prob HV → Def HV		Def HV → Insuff Info					Def HV → Prob HV	90
Hammer 12"	Prob MV → Def MV	Def HV → Prob MV				Def MV → Insuff Info			Insuff Info → Prob MV		70
Crow Bar 12"		Prob MV → Prob HV		Prob MV → Prob HV	Def HV → Prob HV	Prob MV → Prob HV		Prob MV → Insuff Info		Def MV → Prob MV	60
.357 Magnum 12"			Def HV → Prob HV								100
Consistency (%):	80	40	100	80	80	40	100	80	80	100	

Figure 8: Response matrices indicating consistency in assessment of the five duplicated spatter patterns. Green denotes no change in response (i.e., the same pattern was assessed the same twice). Yellow denotes a change in confidence level from "probably" to "definitely" or vice versa. Red denotes a change in assessment, e.g., from medium to high velocity. Numbers at bottom and far right indicate the percent of consistent responses, i.e., based on the number of green and yellow squares. **(a)** Consistency matrix for the student cohort. **(b)** Consistency matrix for the analyst cohort.

DISSEMINATION OF RESEARCH FINDINGS

The PI presented preliminary results, by invitation, to the American Society of Crime Lab Directors:

> "Quantitative Analysis of High Velocity Impact Bloodstain Patterns." Prof. William Ristenpart. Poster Presentation, American Society of Crime Lab Directors, Denver, CO (September 21, 2011).

The PI also presented further preliminary results during the 2012 Annual Meeting of the American Academy of Forensic Sciences (AAFS), at the NIJ Grantees' Meeting:

> "Quantitative Analysis of High Velocity Bloodstain Patterns: A Double Blind Investigation of Impact Velocity Assessment." Prof. William Ristenpart. Oral Presentation, American Academy of Forensic Sciences, NIJ Grantees Meeting, Atlanta, GA (February 21, 2012).

At the same meeting, one of the graduate students on the project presented a poster at the student poster session:

> "Quantitative Analysis of High and Medium Velocity Impact Bloodstain Patterns." Ms. Sonya Siu, Poster Presentation, American Academy of Forensic Sciences, Student Poster Session, Atlanta, GA (February 21, 2012).

Following the final grant report, the research will be submitted as two separate publications in the *Journal of Forensic Sciences* (reflecting the two main parts of this report). The results will also be forwarded to, and likely presented at, the Scientific Working Group for Blood Stain Pattern Analysis (SWGSTAIN). This working group consists of professionals from the bloodstain interpretation community with the goal to identify and recommend "best practice" for bloodstain analysis. We believe the results of this study will help inform best practice for the blood stain analysis community.