NISTIR 8171

Contactless Fingerprint Devices Usability Test

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National Institute of Standards and Technology
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EXECUTIVE SUMMARY

The United States Department of Homeland Security (DHS) relies on the use of biometrics as an important component of its mission to make America safer. Customs and Border Protection (CBP) traveler inspections within Federal Inspection Service (FIS) locations at airports as well as land borders rely on biometric technologies to identify and inspect foreign travelers entering the United States. To meet their mission of securing borders, DHS is committed to identifying and deploying cutting-edge technologies.

However, in the employment of contact fingerprint collection technology many risks are involved in the use of these systems, such as the transmission of pathogens by the contaminated contact surface of the scanner as well as increased collection times resulting in slower throughput in the overall process. Touchless systems address these concerns but also introduce new challenges related to human factors that may affect the biometric system performance. To examine these issues, it is necessary to study the usability of the contactless fingerprinting devices in terms of: ergonomics and anthropometrics, affordance, accessibility, and user satisfaction.

Sixty participants volunteered to be part of the study. To limit any potential order bias, three touchless fingerprint devices were presented in a counterbalanced order (i.e., ABC, BCA, CAB, ACB, BAC, and CBA). The order was maintained over three rounds of testing. The test facilitator asked the participants to attempt to capture their own prints on each device across the three rounds of testing. For the first round of testing, participants attempted to capture their fingerprints without any instructions. On the second round, participants watched an instructional video for each device and then attempted to capture their fingerprints. The test facilitator demonstrated proper use during the third round of testing, and another staff member verified the print capture and image quality.

All participants had their fingerprints captured previously using a device that required physical contact with the scanner. Devices A, B, and C were all touchless in nature so that participants did not touch any of the devices to collect their fingerprints and given their previous experience that was not what they expected to do. None of the participants were able to capture their fingerprints successfully using Device A (10%) and Device B (3%) during the first round of testing, and participants were more successful with Device C (53%). There were no instructions provided during the first round of testing and without assistance participants did not know how to capture their fingerprints. As a result, many of them attempted to capture their fingerprints by touching the devices as they had in the past with a traditional fingerprint scanner. Participants were also not sure if they were successful or not due to the lack of feedback. Affordance (i.e., clues about how the device should be used) with these devices was limited.

Instruction was provided in rounds two and three. In round two, participants watched a video of a NIST researcher performing the correct behavior for successful capture. After watching the video, participants were instructed to attempt collection of their fingerprints. In round three, the test facilitator demonstrated the proper us of each of the scanners. Participants attempted collection and a test facilitator notified the participant if the prints collection was successful. As a result, success rates increased for all devices and across each round of testing.

The fingerprints acquired under supervised use of the touchless devices were compared to exemplar plain impressions taken from each subject and recorded using a legacy FTIR[1] scanner. Out of the two sets of plain impressions from each subject, one set served as the exemplar for comparison against each touchless impression and the control case for metrics involving comparison for interoperability assessment.

Of the measurements of image characteristics, those of particular interest were aimed at measuring interoperability of touchless acquisitions with contact plain impressions. In this regard, we examined correlation of ridge orientation, deviation in placement of corresponding minutiae, and fingerprint similarity using a state-of-the-art pattern matcher. While generally inferior to comparisons of contact-to-contact, results suggest that at least two of the three contactless devices should be interoperable with legacy contact capture devices, given use of a modern matcher.

Some difficulty should be expected with human visual comparison using the gray-scale or binary image rendered from the original photographic capture, as errors in the rendering result in loss of ridge continuity entirely or contrast reversals in which ridge and valley renderings become confounded. Ambiguity over ridge vs. furrow can reverse bifurcations and ridge endings or even offset locations of features such that visual correlation of features becomes more difficult, requiring more time to confirm. A matcher configured so as to ignore the distinction between the two main identification features and to provide robustness to small displacements of features would likely suffer little from the ambiguity. Visual comparison of touchless and contact images in order to select control points (minutiae) for image registration confirmed the difficulty of human examination. By contrast, match scores for touchless-to-contact were lower than those for contact-to-contact comparison, but still well above a baseline match score among known non-matching images. These results were based on a small sample and, thus, tentative. However, the finding is encouraging for the employment of touchless fingerprint technology.

[1] Frustrated Total Internal Reflection (FTIR) is the optical mechanism by which many modern contact fingerprint acquisition devices capture digital fingerprints directly via contact of the friction ridge surface with the surface of a prism.

1 INTRODUCTION

The United States Department of Homeland Security (DHS) relies on the use of biometrics as an important component of its mission to make America safer. For this mission, DHS is committed to using cutting-edge technologies of which biometrics are an important part. Customs and Border Protection (CBP) traveler inspections within Federal Inspection Service (FIS) locations at airports as well as land borders rely on biometric technologies to identify and inspect foreign travelers entering the United States.

The DHS Science and Technology Directorate (S&T) capitalizes on technological advancements to deliver effective and innovative technological tools to help protect the homeland. S&T conducts both basic and applied research, demonstration, testing and evaluation activities for DHS. DHS S&T funded this project and a previous project to research technologies that could be used to acquire fingerprints without physical contact with the device.

Current applications of biometric technologies are limited to state-of-industry biometric collection devices. These include primarily optical and capacitive discharge capture equipment for contact-based electronic fingerprint collection. However, many risks are involved in the use of these systems, such as the transmission of pathogens by the contact surface of the scanner and the new biometric sample collection tasks increased collection times anywhere from 15 seconds to over a minute to the normal processes. As a result, rather than support the collection process, this additional time requirement resulted in a slower throughput in the overall process.

Previously, DHS funded two research projects for fingerprint acquisition without physical contact with the scanner. These systems use both structured light illumination and optical spectrum with focus diversity. The goal of these systems is to develop a new generation of biometric capture devices that don't require physical contact with the biometric sensor. The devices are designed to rapidly and efficiently capture high-resolution images of fingerprints. As a result, the approach to fingerprint capture solves several challenges caused by the previous scanners but also introduces several new challenges that need to be addressed.

Some of these new challenges are related to human factors that may affect the biometric system performance, that is, how the human interfaces with the technology. To examine these issues, it is necessary to study the usability of the contactless fingerprinting devices in terms of: ergonomics and anthropometrics, affordance, accessibility, and user satisfaction. Input on human factors will result in a more robust system that increases human performance both in timing and quality and encourages human acceptance.

According to ISO 9241-11, usability is "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [1]. Efficiency, effectiveness, and user satisfaction are defined as:

- *Efficiency* is a measure of the resources expended in relation to the accuracy and completeness with which users achieve goals. Efficiency is related to productivity and is generally measured as task time.
- *Effectiveness* is a measure of accuracy and completeness with which users achieve specified goals. Common metrics include completion rate and number of errors.

- *User satisfaction* is the degree to which the product meets the users' expectations – a subjective response in terms of ease of use, satisfaction, and usefulness.

This report describes the usability tests performed measuring three dimensions of usability on three contactless fingerprint devices and the comparison of images captured on the devices and compared to the current collection system.

2 METHOD

2.1 PARTICIPANTS

Sixty National Institute of Standards and Technology (NIST) employees volunteered to participate in the study. The group of participants included 36 males (60%) and 24 (40%) females with ages ranging from 18 to 70+ as shown in Figure 1. Slightly over half of the participants were ages 18-25, accounted for by the number of summer students who chose to be involved in the study.

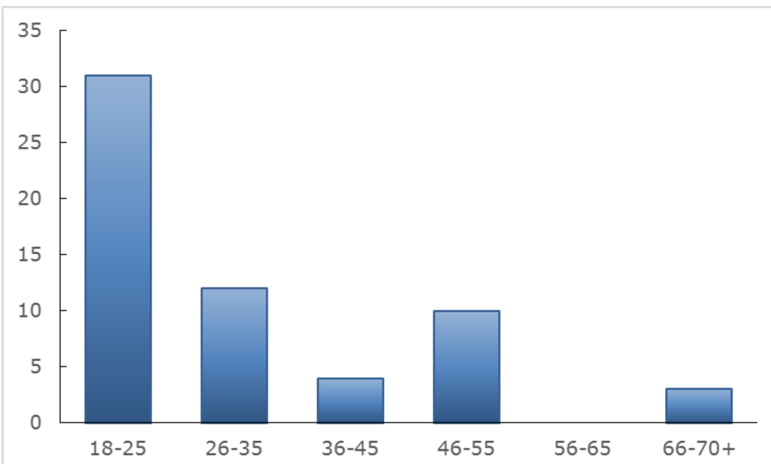

Figure 1 . Participant Age Range

Handedness – Participants were asked to select their dominant hand either, left, right, or ambidextrous. Four (7%) were left-handed and 56 (93%) were right-handed, slightly more than the 87% of the general population who are right-handed [2].

Country of Origin - Participants were asked their country of origin with 49 out of the 60 participants from the United States. Table 1 shows the country of origin.

Table 1. Country of Origin

US	China	UK	Puerto Rico	Vietnam	Canada	New Zealand	St. Lucia	Total
49	5	1	1	1	1	1	1	60

Previous Fingerprint Capture Experience – Participants were asked if they used a fingerprint scanner before excluding smartphone fingerprint scanners. If they answered yes they were asked to select the number of times (i.e., 1, 2, 3, 4 or more) they had used one. Only six participants answered that they had not used a fingerprint scanner before. It is important to note that all participants were NIST employees and all employees are fingerprinted as part of the NIST employment process. Table 2 shows the number of times that participants selected for having their fingerprints scanned.

Table 2. Number of Times Fingerprints Scanner Previously

1 Time	2 Times	3 Times	4 or More Times	Total
15	21	4	14	54

Smart Phone Fingerprint Scan Use – Participants were asked if they have used the fingerprint scan feature on their smart phone. If they answered 'Yes' they were asked which smart phone they had used the feature on. Forty participants answered "Yes" to using the scan feature on their smartphone and 20 participants answered "No". Table 3 shows the type of phone that the participant used the scan feature. [2]

Table 3. Type of Phone Participant's Used Scan Feature

Apple	Samsung	LG	Nexus	Total
29	7	1	3	40

2.2 MATERIALS

The materials for the test included:

- 3 contactless fingerprint scanners (referred to as Device A, Device B, Device C)[3]
- Contact scanner
- Bar code scanner
- Bar codes for each participant and a bar code for each of the three devices
- A table for two of the devices (one device was stand-alone)
- Two floor mats with silhouettes of yellow feet to indicate where the participant should stand
- Three sets of video instructions (i.e., one video for each of the devices)
- 21" computer monitor (used to display videos)
- Computer with monitor (used to launch videos)
- Computer with monitor (used to run software for contact scanner)
- Computer with monitor (used to assess quality of captured prints by the three touchless devices)
- Custom software
- Video and audio recording equipment
- Traditional contact scanner
- Information sheet (see Attachment A)

[2] Specific hardware and software products identified in this report were used in order to perform the evaluations described. In no case does identification imply recommendations or endorsement by the National Institute of Standards and Technology, nor does it imply that the products and equipment identified are necessarily the best available for the purpose.

- Demographic questionnaire (see Attachment B)
- Post-task questionnaire for each device and each round of testing (see Attachment D)

2.2.1 Contactless Scanner Device A

Device A contactless fingerprint scanner used in this research measured 13.5 inches (34.29 cm) x 4.5 inches (11.43 cm) x 10.5 inches (26.67cm). [measurements are height x width x depth]. The opening to pass the fingers through, highlighted in white (see Figure 2), measured 1.5 inches (3.81 cm) narrowing to 1 inch (2.54 cm) in height and 4 inches (10.16 cm) in depth. The glass panel on the shelf was illuminated when ready to collect prints.

Figure 2. Contactless Fingerprint Scanner Device A

All instructional and directional markings (e.g., arrows, etc.) were covered with white stickers (see Figure 3). To capture prints, participants passed their fingers between the flange (i.e., top) and the glass panel. The green light would turn off after the participant passed their fingers through the opening and light again after the fingers finished the pass through. The device did not provide successful or failure fingerprint capture status. Participants had to notice the green light under the shield and detect that it had turned off and then back on.

Figure 3. Covered Areas on Contactless Fingerprint Scanner Device A

The images captured by the device were saved on a computer used in the test. A custom capture application was used to control the fingerprint scanner and collect the digital images of the participant’s fingerprints.

2.2.2 Contactless Device B

Contactless fingerprint scanner Device B measured 65.5 inches (166.37 cm) x 12 inches (30.48 cm) x 43 inches (109.22 cm). The lighted opening to pass the hand through (see figure 4) measured 6.5 inches (16.51 cm) x 7 inches (17.78 cm). If the hand was passed through the lighted opening so that the camera could detect the hand, the device would ding and the green light would flash. However, if the hand was not passed through the opening so that the hand was detected, the green light turned red and the device made a discouraging beep sound.

All instructional and identifying information was covered by white paper (see Figures 4 & 5). The only feedback provided was the green light blink and ding indicating that the device had detected a hand and taken a picture of the hand; or the green light turning from green to red and a beep if the participant tried an action that led to non-detection of the fingers by the device. The device did not provide status on success or failure to capture a quality image. The images captured by the device were saved on a computer used in the test. A custom capture application was used to control the fingerprint scanner and collect the digital images of the participant’s fingerprints.

Figure 4 & 5. Contactless Fingerprint Scanner Device B & Covered Areas Device B

2.2.3 Contactless Device C

Contactless scanner Device C measured 8.5 inches (21.59 cm) x 6.5 inches (16.51 cm) x 4.75 inches (12.065 cm). The opening marked by the white box shown in Figure 6 measured 4.75 inches (12.065 cm) x 1.75 inches (4/445 cm) x (4 inches 10.16 cm).

To have their fingerprints captured, the participant would insert their fingers into the opening of the black box. When the device detected their fingers, the camera inside the box would flash. There was no feedback indicating success or failure of a print capture except for the camera flash that may have been difficult for the participant to notice.

The images captured by the device were saved on a computer used in the test. A custom capture application was used to control the fingerprint scanner and collect the digital images of the participant's fingerprints.

Figure 6. Contactless Fingerprint Scanner C

2.2.4 Contact Scanner

The contact scanner used to capture fingerprints for image quality purposes, measured 5.75 inches (14.61 cm) x 5 inches (12.7 cm) x 6 inches (15.24 cm). On the top of the scanner (see Figure 7) was a glass platen that was the contact surface where the participants placed their fingers for fingerprint capture. The glass platen measured 3 inches (7.62 cm) x 3.5 inches (8.89 cm).

Figure 7. Traditional Fingerprint Scanner

Just above the platen was a line of four Light Emitting Diodes (LEDs) with each capable of emitting a red or green light. On each side of the platen were two indicators corresponding to a right slap, right thumb (indicators on right side), and two indicators corresponding to a left slap and left thumb (indicators on the left side). The indicators light up to indicate which fingers or thumb the participant was supposed to capture. The scanner also emitted audible tones (i.e., beeps) whenever it successfully captured a print image.

A custom capture application was used to control the fingerprint scanner and collect the digital images of the participant's fingerprints. Participants were instructed to capture the four fingers on their right hand only for the image quality test. Two right hand, four finger prints were captured for each participant. One of the test facilitators guided the participants through the capture process to ensure a successful capture.

2.2.3 Instructional Materials

Each of the touchless fingerprint scanner devices had an associated instructional video. A NIST staff member recorded instructional videos for each device. The videos showed the staff member demonstrating the correct technique to capture four fingerprints from the right hand only. Participants watched the videos during the second round of testing and then attempted to collect their fingerprints as demonstrated in the video. Participants could watch the video as many times as they wished.

During the third round of testing, the test facilitator demonstrated the correct use of each of the devices. After watching the test facilitator, participants attempted to collect their prints.

2.3 Experimental Methodology

We used a counterbalanced design (i.e., device order: ABC, BCA, CAB, ACB, BAC, and CBA) across three rounds of testing. Each participant was assigned to one of the ordering sequences. When the participant arrived at the laboratory, the test facilitator greeted them and thanked them for their participation. The facilitator gave the participant a copy of the information sheet and reviewed the information (see Appendix A). Participants had the option to read the information and/or take a copy for later use. The facilitator asked the participant if they had any questions before beginning the testing and provided the demographic questionnaire.

After the participant completed the demographic questionnaire (see Appendix B) the test facilitator escorted them to the lab where the touchless fingerprint scanners were located. Each of the touchless fingerprint scanner devices was hidden from the participant's view by a partition, and they did not see the device until they were instructed to attempt fingerprint capture with the device.

Each participant was assigned a bar code. Each participant session was captured using audio and video equipment. For each round, the test facilitator instructed the participant to stand on the mat at the front of the lab located in front of the partitions until they were ready to attempt capture of their prints. When they signaled they were ready, the test facilitator scanned their participant barcode and instructed them to walk around the partition and begin using the assigned device. When they signaled that they were finished, the test facilitator scanned the device bar code stop for the device the participant was using. The participant number's barcode start scan and the device barcode stop scan provided an estimate of the participant's interaction time with each device. Participants completed a post-task survey (see Appendix C) after they completed their interaction with each device across each of the rounds of testing.

For the first round of testing, the test facilitator asked the participant to stand on the mat that was located inside the testing room. The test facilitator instructed the participant that they were to capture their prints as best they saw fit and no other instructions were provided. This process continued until the participant had attempted to capture their fingerprints on each of the three touchless fingerprint scanner devices.

For the second round, participants continued with the assigned device order. However, this time they watched a video demonstrating the proper use of the device. After the initial viewing, the facilitator asked if they would like to see the video again. When they were ready, they again signaled the instructor, the facilitator scanned the participant’s barcode to begin timing and the participant attempted to capture their fingerprints. The participant signaled when they were finished and the facilitator scanned the device stop barcode. Participants again completed the post-task questionnaire. This process continued until the participant watched all the videos, attempted to capture their prints, and completed the post-task questionnaire for the three devices.

The purpose of the third round of testing was to get a successful quality capture of the participant’s right-hand four finger print. The device order and process remained the same, except this time the test facilitator demonstrated the proper use of the device and assisted the participant in capturing four fingers on their right hand. Another staff member checked the prints and informed the facilitator and the participant about the status of the prints. The process continued until successful prints were captured on each of the three devices.

After the third round, the facilitator escorted the participant back to the main testing lab. The participant completed the post-test satisfaction questionnaire (see Appendix D). The facilitator answered any questions the participant had and then another staff member assisted the participant in capturing a right-hand, four finger capture on the contact scanner for quality comparison purposes. After the collection was completed, the facilitator thanked the individual for their participation.

3 RESULTS

This section describes the results of the usability tests performed on the three touchless fingerprint scanner devices.

3.1 Usability Metrics

The study was designed to test three fingerprint scanner devices and measure their usability in terms of efficiency, effectiveness, and user satisfaction. Definitions for the three usability dimensions are described below.

3.1.1 Efficiency

The efficiency of each device was measured by how long it took for participants to complete the fingerprinting capture.

3.1.2 Effectiveness

Effectiveness was measured by both task success and the quality of the captured prints. A successfully completed task was defined as the participant presenting their fingers in such a way that the device was able to capture fingerprint images.

3.1.3 User Satisfaction

User satisfaction was measured by to what extent if any, the participant found a given device intuitive, easy to use, fast, and how well it provided feedback. The post-task questionnaire was used to capture user satisfaction data (see Appendix D).

The questionnaire contained five questions including: rank the fingerprint scanners in order of how easy they were to use then justify your answer; fingerprint scanner preference and why; where improvements were needed and if so what improvements; and one question about whether the device video was helpful.

3.2 Number of Attempts to Capture Prints

A NIST researcher counted the number of times a participant attempted to capture their fingerprints by watching the participant videos. Participants' previous experience and thus their mental models for fingerprint capture involved touching a surface on the device.

For most first round attempts, participants were not given instructions so they tried to capture their prints by touching a surface area on the device. Participants had more attempts on Device B than the other two devices. Both Device A and Device C had limited surface area on which a participant could touch whereas Device B was much larger than the other devices and had more surface area on which the participants could touch. Clearly, after participants watched the instructional video the number of attempts decreased. In round three, attempts increased slightly across the three devices. Participants attempted to capture their fingerprints until it appeared there was an image that could be used for comparison purposes. Figure 8 shows the mean number of attempts to capture prints for each device across the three rounds of testing.

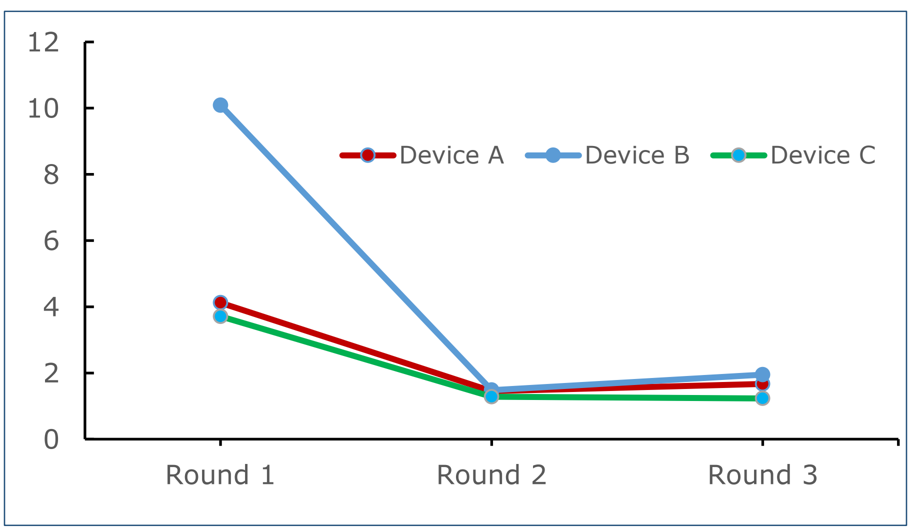

Figure 8. Mean Number of Attempts to Capture Prints Using Each Device Across Rounds

3.3. Efficiency – Fingerprint Capture Times

We captured approximate time-on-task for each of the devices across each of the rounds of testing. Participants and devices each had an assigned bar code. For each round of testing, the test facilitator scanned the participant's bar code when the participant signaled they were ready to capture their prints on the device. When the participant signaled they were finished using the device, the facilitator scanned the assigned device bar code stop. The start and stop bar code scans were used to calculate approximate average time on task.

For round 1, Device B had the highest mean time on task of 52.6 seconds with Device A (mean = 30.3 seconds) and C (mean = 29.2 seconds) having similar time on tasks. Time-on-task decreased across the rounds as participants became familiar with the process. Time on task for Device A decreased by 18 seconds from round 1 to round 2, Device B had a reduction by 41 seconds, and Device C experienced a 19.9 second reduction in time on task. Table 4. shows the average time on task in seconds that it took for participants to complete the fingerprinting tasks with the three contactless scanners.

Table 4. Time on Task

Device	Round 1 (no instructions)	Round 2 (video)	Round 3 (Verbal instructions)
Device A	30.3 *s*	12.3 *s*	8.3 *s*
Device B	52.6 *s*	11.6 *s*	5.7 *s*
Device C	29.2 s	9.3 *s*	5.7 *s*

3.4 Effectiveness – Successful Print Capture

A successful capture is defined as when the device not only produces images of all four fingers from the participant's right hand, but also that the images are of sufficient quality according to the metrics described in Section 4. It should be noted that even though participants were guided by a test facilitator during Round 3, the quality of the resulting captures were not always found to be of sufficient quality in post-capture analysis. Table 5 shows the number of participants who had their fingerprints captured by each task across each of the three rounds of testing.

Table 5. Successful Capture

Device	Round 1 (no instructions)	Round 2 (video)	Round 3 (Verbal instructions
Device A	6 (10%)	44 (73%)	49 (82%)
Device B	2 (3%)	27 (45%)	42 (70%)
Device C	32 (53%)	47 (78%)	47 (78%)

3.5 Successful Behavior

We defined successful behavior as the participant approaching the device and performing a behavior that would lead to capturing an image of their fingerprints. We did not define this as a successful capture because the only way to know if the participant was successful in capturing their prints was to look at the images collected on each round of testing. It is important to note that even when the participants presented their fingers correctly, the device did not always capture an image of the participant's fingerprints. It should also be noted that there were some cases where a participant would perform a behavior different than what we previously defined as successful and still resulted in a successful capture. An example of this might be a participant passing their hand through a device's capture area in the opposite direction, triggering a capture which turned out to be successful.

Round three results are not included because the test facilitator demonstrated the correct capture technique and the participant continued to attempt capture until other team members validated the capture. Participants did not receive any instructions on how to use the device prior to attempting to collect their fingerprints

3.5.1 Device A – In round one, only one participant performed the behavior required to have their fingerprints captured. However, that participant had used a similar device at school so they knew what to do. In comparison, after watching a video demonstration, all but one participant performed the correct behavior required to capture an image of their fingerprints.

3.5.2 Device B – None of participants performed the behavior required to capture an image of the participant's fingerprints. In the second round of testing, 57 of the 60 participants (95%) performed the correct behavior to capture an image of their fingerprints.

3.5.3 Device C – In round one, 41 (68%) of the participants performed the behavior required to capture an image of their fingerprints. In round 2, all but one of the participants performed the behavior required to capture an image of the participant's fingerprints. Table 6 shows the number of participants who attempted the behavior that would result in an image capture of their fingerprints.

Table 6. Successful Behavior

Device	Yes	No	Missing
Device A			
Round 1	1	59	0
Round 2	59	1	0
Device B			
Round 1	0	59	1
Round 2	57	3	0
Device C			
Round 1	41	18	1
Round 2	59	1	0

3.6 Speed of Device
After participants interacted with the each of the devices in each of the three rounds of testing, they were asked their perceptions of the speed of each device. They chose from: "too fast, too slow, and appropriate speed". Some of the participants failed to answer the question. Table 7 shows the participants' rating for device speed across testing rounds. The majority of participants rated all device speeds as appropriate across the three trials. Appropriate speed of device ratings increased as participants had more experience with the devices. Table 7 shows the device speed responses.

3.7 Device Ready to Use
For each device across each round of testing, participants were asked if they could tell that the scanner was ready to accept their fingerprints. Answer choices were: "No, I couldn't tell;" "Yes, I could tell;" and "I was unsure."

Table 7. Speed of Device

Device	Too Fast	Too Slow	Appropriate	No Answer	Total
Device A					
Round 1	9 (15%)	8 (13%)	42 (70%)	1	**60**
Round 2	7 (12%)	2 (3%)	50 (83%)	1	**60**
Round 3	-	2 3%)	58 97%)	-	**60**
Device B					
Round 1	9 (15%)	10 (7%)	38 (63%)	3	**60**
Round 2	7 (12%)	1	51 (85%)	1	**60**
Round 3	1	4 (7%)	55 (92%)	-	**60**
Device C					
Round 1	14 (23%)	1	43 (72%)	2	**60**
Round 2	9 (15%)	-	49 (82%)	2	**60**
Round 3	3 (5%)	-	57 (95%)	1	**60**

In round one for both Devices A (72%) and B (55%), participants responded that yes they could tell that the device was ready. Only 12% of respondent answered that they could tell that Device C was ready.

In round two the majority of participants (95%) responded that they could tell that both Devices A and B were ready to use. Less than half of the respondents (38%) answered that they could tell that Device C was ready to use.

For round three, both devices A and B also had over 90% of participants respond that they could tell the device was ready to use. However, less than half of the respondents (45%) answered that they could tell that Device C was ready to use. Table 8 shows the participant responses for device ready.

Table 8. Device Ready Status

Device	No, I couldn't tell	Yes, I could tell	I was unsure	No Answer	Total
Device A					
Round 1	9 (15%)	43 (72%)	8 (13%)		**60**
Round 2	2 (3%)	57 (95%)	1		**60**
Round 3	3 (5%)	56 (93%)	1		**60**
Device B					
Round 1	14 (23%)	33 (55%)	13 (22%)		**60**
Round 2	1	57 (95%)	1	1	**60**
Round 3	1	59 (98%)			**60**
Device C					
Round 1	38 (63%)	7 (12%)	15 (25%)		**60**
Round 2	29 (48%)	23 (38%)	7 (12%)	1	**60**
Round 3	27 (45%)	27 (45%)	6 (10%)		**60**

Quite possibly the light for both devices A & B was either brighter or easier to detect than for Device C. Device A had a green light that could be seen from the side of the device and Device B has a blue light that was in full view when the participant walked up to the device. Device C would flash only when the device detected the participant's finger(s) and the camera was housed inside the box exterior. Participants assumed that the device camera light on each of the devices provided the device ready status.

3.8 Fingerprint Successfully Captured

For each of the devices and after each of the three rounds of testing participants answered whether they thought their fingerprints were successfully captured. Participants choices were: "No, I couldn't tell;" "Yes, I could tell;" "I was unsure." Some of the participants chose not to answer the question.

For the first round of testing, less than half of the participants responded that they could tell that their fingerprints were successfully captured on each of the devices. For Device A only 22 (37%) answered yes that they could tell, for Device B, 47% said yes they could tell, and for Device C only 16 (27%) said yes they could tell their fingerprints were successfully captured.

After watching a video demonstrating how to capture fingerprints on each device, the number of participants answering "Yes, I could tell" increased slightly for Device A from 37% to 42%; Devices B from 47% to 80%; and for C from 27% to 67%.

In round 3, the test facilitator demonstrated proper use of the devices. The "Yes, I could tell" for Device A increased again in the third round of testing from 42% in round 2 to up to 60% in round 3. However, this was not the case for Devices B and C with Device B dropping from 80% to 60% and Device C dropping from 67% to 62%. Table 9 shows the participant responses.

Table 9. Fingerprint Capture Successful

Device	No, I couldn't tell	Yes, I could tell	I was unsure	No Answer	Total
Device A					
Round 1	21 (35%)	22 (37%)	17 (28%)		**60**
Round 2	18 (30%)	25 (42%)	17 (28%)		**60**
Round 3	16 (27%)	36 (60%)	8 (13%)		**60**
Device B					
Round 1	16 (27%)	28 (47%)	16 (27%)		**60**
Round 2	5 (8%)	48 (80%)	6 (10%)	1	**60**
Round 3	14 (23%)	37 (62%)	9 (15%)		**60**
Device C					
Round 1	26 (43%)	16 (27%)	18 (30%)		**60**
Round 2	11 (18%)	40 (67%)	7 (12%)	2	**60**
Round 3	12 (20%)	37 (62%)	11 (18%)		**60**

3.9 Instructions

No instructions were provided during the first round of testing and participants were instructed to walk up and use the device as they saw fit. For the second round of testing, participants watched a video only (i.e., no sound included) of one of the NIST researchers demonstrating proper use for each of the devices prior to attempting capture of their fingerprints. In round three, the test facilitator demonstrated proper use of each of the devices. For each round of testing after attempting to capture their prints on each of the devices, participants rated whether they agreed/disagreed (i.e., strongly agree, agree, disagree, and strongly disagree) with the question whether they would have known what to do to capture their fingerprint without watching the video.

In the first round of testing, 69% of participants agreed (agree + strongly agree) that they knew what to do to capture their fingerprints without instructions using Device A. For Device B, 35% agreed that they knew what to do without instructions, and for Device C, 55% agreed that they knew what to do to capture their fingerprints without instructions. Clearly the successful capture rates show that without training, participants did not know how to successfully capture their fingerprints (see Table 5).

In round two, participants watched videos demonstrating proper use of each of the devices. The percent of participants who agreed that they would know what to do without instructions decreased from 69% to 25% of participants. For Device B the percent decreased slightly from 35% to 32% of participants who disagreed to knowing what to do to capture their fingerprints without instructions. The same is the case for Device C as the percent of participants who disagreed that they would know what to do without instructions decreased from 55% to 50%.

In round three, the test facilitator demonstrated proper use of each of the devices. Participants attempted to capture their fingerprints until the test facilitator validated a successful capture. For Device A, 31% of participants disagreed that they would know what to do to capture their fingerprints. For Device B, 30% of participants disagreed they would know what to do to capture their fingerprints and for Device C, 55% agreed that they would know what to do to capture their fingerprints. Table 10 shows the ratings for knowing what to do to capture prints without instructions.

Table 10. Ratings for Agreement to Knowing What to Do to Capture Fingerprints without Instructions

Device	Strongly Agree	Agree	Disagree	Strongly Disagree
Device A				
Round 1	10 (17%)	31 (52%)	13 (22%)	6 (10%)
Round 2	8 (13%)	7 (12%)	23 (38%)	22 (37%)
Round 3	8 (13%)	11 (18%)	30 (50%)	11 (18%)
Device B				
Round 1	4 (7%)	17 (28%)	17 (28%)	22 (37%)
Round 2	9 (15%)	10 (17%)	19 (32%)	22 (37%)
Round 3	10 (17%)	8 (13%)	27 (45%)	15 (25%)
Device C				
Round 1	2 (3%)	31 (52%)	16 (27%)	11 (18%)
Round 2	8 (13%)	22 (37%)	23 (38%)	7 (12%)
Round 3	12 (20%)	21 (35%)	23 (38%)	4 (7%)

3.10 Describe Experience with Devices

After each attempt at capturing their fingerprints and for each round of testing, participants provided feedback about their experience using the device.

3.10.1 Device A

Many of the participants thought that Device A was similar to the fingerprint scanning device that they had used previously. They proceeded to press their fingers on the glass/platen and believed that they had used the device correctly. However, after watching the video, they were somewhat surprised at how the device worked. This is clear from their descriptions of their experience in round 2 after watching an instructional video.

Participant 1:
Round 1: "Straightforward experience on how to capture prints. Only misconception was how many prints to capture."
Round 2: "Completely different from my previous train of thought. Very straightforward with instructions."

Participant 18:
Round 1: "Looks like any other scanner I have used. Because of that it makes it easy to use."
Round 2: "Not as straight forward as the look of your typical scanner. Confusing, after video it was clear."

Participant 27:
Round 1: "More intuitive because of the surface to place hands."
Round 2: "Easy to use. Based on current scanners used today, not intuitive. Looks like you are supposed to place thumbs on surface."

Participant 60:
Round 1: "This instrument seemed more intuitive but it was unclear if I was using it properly/getting a good image."
Round 2: "Not at all what it seems like!"

3.10.2 Device B

Participants generally found Device B confusing to use. But they agreed that after watching the video it was simpler to use, found it cool and futuristic.

Participant 9:
Round 1: "Could not figure out the appropriate method for capture was a somewhat frustrating experience."
Round 2: "Seems a bit biased for right handed people. Cool idea though."

Participant 19:
Round 1: "Confusing, walked in and had no idea where to place hand. This is weird."
Round 2: "Simple."

Participant 32:
Round 1: "Did not have a clue how it worked. It was a great piece of art."
Round 2: "Much clearer after the video."

Participant 42:
Round 1: "This device without instructions is very bothersome."
Round 2: "Would have never figured it out without instructions."

3.10.3 Device C

Participants found Device C more intuitive then the other devices but will still confused at first about how to capture their prints and unsure if the device captured their fingerprints due to the lack of feedback.

Participant 13:
Round 1: "Confusing, ambiguous"
Round 2: "Slightly ambiguous, simple but no confirmation."

Participant 15:
Round 1: "Alien, black box and no idea how it works. Very intuitive to stick hand in. But no feedback if correct."
Round 2: "After video can capture (more intuitive) still don't know if it was successful."

Participant 27:
Round 1: "Obvious general vicinity where to place thumbs. Not intuitive on how far to place thumbs, or if I am supposed to touch something."
Round 2: "With video, very straight forward. No indication of success or failed capture. Don't know if I can stick a piece of wood in and if it would still capture and flash blue."

Participant 60:
Round 1: "It was unclear how to take a scan of my fingerprints and no info given on success or failure. Not a great unit without instructions."
Round 2: "It was fast but provides minimal feedback."

3.11 Ratings for Understanding What to do After Watching the Video

In round two, participants watched a video prior to attempting to capture their fingerprints on each of the three devices. After attempting the capture, they were asked to rate agreement (i.e., strongly agree, agree, disagree, strongly disagree) to the question: "I could understand what to do after watching the video." Most participants agreed (strongly agree + agree) that they understood what to do after watching the videos. For Device A, 85% of participants agreed that they understood what to do. For Device B, 87% of participants agreed and for Device C, 95% of participants agreed that they knew what to do after watching the video. Table 11 shows the ratings.

Table 11. Ratings for Understanding What to do After Watching Videos

Device	Strongly Agree	Agree	Disagree	Strongly Disagree	No Answer	Total
Device A	38 (63%)	13 (22%)	2 (3%)	6 (10%)	1	60
Device B	43 (72%)	9 (15%)	0	6 (10%)	2	60
Device C	41 (68%)	16 (27%)	0	2 (3%)	1	60

3.11 Video Clarity and Questions After Watching Videos

Participants watched three separate videos in round 2 of testing that demonstrated the use of each of the devices. We were interested in the clarity of the video and whether the participant continued to have questions after watching each of the videos.

3.11.1 Video Clarity

For each device, participants answered whether the video was clear about how to collect their fingerprints (i.e., video was clear, video was not clear, or unsure). The first 30 (i.e., 1-30) participants answered the question.

For each device, the majority of participants answered that the videos were clear and none of the participants answered that the videos were not clear. For Device A, 87% of participants answered that the video was clear. Over 90% of participants answered the video was clear for both Devices B (97%) and C (90%). Table 12 shows the number and percent of participant responses.

Table 12. Video Clarity

Device	Video was Clear	Video was Not Clear	Unsure
Device A	26 (87%)	0	4 (13%)
Device B	29 (97%)	0	1 (3%)
Device C	27 (90%)	0	3 (10%)

3.11.2 Questions After Watching Video

We wanted to understand what questions, if any, participants had after watching the video. So participant 31-60 were asked whether they still had questions after watching the video and, if they did, what were the questions. Only a few participants had questions about capturing their fingerprints after watching the videos. Only seven (23%) of participants had questions after watching the video for Device A and for Devices B & C six (20%) has questions after watching the video for both devices. Table 13 shows the number and percent of participants answering yes/no to the question.

Table 13. Questions After Watching Instructional Video

Device	Yes	No	No Answer
Device A	7 (23%)	22 (73%)	1
Device B	6 (20%)	23 (77%)	1
Device C	6 (20%)	24 (80%)	

3.11.3 Questions About Video

We asked the participants who answered yes to having questions after watching the video, what questions they had. Typically, questions were about how to tell fingerprints were captured successfully and how many fingers or thumbs were required. The questions are summarized below.

Questions about Device A included:

- How fast should hand move or can it more too fast?
- Bi-directional hand swiping allowed
- How do you know prints are captured successfully?

- Do I scan my thumbs as well as four fingers?
- Does depth matter?

Questions about Device B included:

- How fast or slow should the hand move through the device
- Does the height of the hand matter?
- Should you stop after the ding and light blinks?
- How do you know you used it correctly?
- Does the chime indicate proper use and print capture?

Questions about Device C included:

- Should fingers be together?
- Does the light blink mean fingerprints are captured?
- Should I capture my thumb print separately?
- How do you know your fingerprints were captured?

3.12 User Satisfaction Post-Test Questionnaire

After participants finished the three rounds of testing, they were asked to complete a post-session satisfaction questionnaire (see Attachment D). They ranked the fingerprint scanners on ease of use, selected the preferred scanner, and suggested improvements (if any). They also answered questions about the ‘helpfulness’ of the videos.

3.12.1 Fingerprint Scanner Rankings, Preferred Scanner, Justification of Preference

Participants ranked the fingerprint scanners on ease of use with one (1) being the easiest to use to (3) three being the most difficult to use. Participants ranked Device B as the easiest to use with 45% of participants selecting the device followed closely by Device C (43% of participants).

Participants also chose the fingerprint scanner they preferred. Half of the participants selected Device B as their preferred fingerprint scanner. Table 14 shows the rankings for the fingerprint scanners and the preferred scanner.

Table 14. Ease of Use Device Rankings and Preferred Device

Device	Ranked 1	Ranked 2	Ranked 3	Preferred Scanner
Device A	9 (15%)	23 (38%)	28 (47%)	11 (18%)
Device B	27 (45%)	17 (28%)	16 (27%)	30 (50%)
Device C	26 (43%)	19 (32%)	15 (25%)	19 (32%)

After participants ranked the devices and selected the preferred scanner, they provided feedback on why they ranked the devices in the order that they did and why they preferred the device that they selected. Reasons for participant’s preference ranged from cool looking to ease of use. Justifications for preference by device were:

Device A

- Ease of use: mentioned 3 times

- Fast: mentioned 3 times
- Screen helped with finger placement: mentioned 1 time
- Only required a wave of the hand: mentioned 1 time
- Can tell status of device when ready and when finished: mentioned 1 time
- Less physically demanding (then B & C): mentioned 1 time

Device B

- Easy to use: mentioned 13 times
- Provides feedback: mentioned 9 times
- Walk through and no stopping: mentioned 8 times
- Coolest looking/futuristic looking: mentioned 6 times
- Quick: mentioned 3 times
- More enjoyable/fun to use: mentioned 2 times
- More completed: mentioned 1 time
- Clear when ready: mentioned 1 time
- No need to touch anything: mentioned 1 time

Device C

- Intuitive/easy to understand/easy to use: mentioned 9 times
- Simple: mentioned 4 times
- Compact: mentioned 2 times
- Doesn't require any motion: mentioned 2 times
- Provided feedback: mentioned 1 time
- No contact with skin: mentioned 1 time
- Fast: mentioned 1 time

3.12.2 Improvements

We asked participants if they thought there were any improvements needed for each device. For all devices, the majority of participants answered 'Yes' improvements were needed for each device. For Device A, 87% of participants answered 'Yes' to improvements needed. For Device B, 68% of participants answered 'Yes' to improvements needed and for Device C, 80% of participants answered 'Yes' to improvements were needed. Table 15 shows the answers for device needs improvements.

Table 15. Device Needs Improvement

Device	Yes	No
Device A	52 (87%)	8 (13%)
Device B	41 (68%)	19 (32%)
Device C	48 (80%)	12 (20%)

If they answered yes, we then asked them what improvements they would suggest. Across all three devices the improvements mentioned most were: some feedback about successful capture, indication that device is ready, and instructions for use. The improvement and the number of times it was mentioned were:

For Device A, participants suggested the following improvements:

- Feedback indicating successful capture (mentioned 24 times)
- A wider opening to accommodate hand size (mentioned 22 times)
- Instructions on how to use the device (mentioned 18 times)
- Indication the status of the device is ready (mentioned 1 time)

For Device B, participants suggested the following improvements:

- Instructions on how to use the device (mentioned 20 times)
- Feedback indicating successful capture (mentioned 7 times)
- Wider opening to accommodate hand size (mentioned 5 times)
- Eliminate some of the walking - too much walking involved (mentioned 4 times)
- Reduce the time to capture an image (mentioned 1 time)
- Size of device is too large (mentioned 3 times)
- Improve accuracy of device (mentioned 1 time)

For Device C, participants suggested the following improvements:

- Feedback indicating successful capture (mentioned 20 times)
- Indication that the device is ready to use (mentioned 17 times)
- Instructions on how to use device (mentioned 12 times)
- Reduce the time to capture fingerprints (mentioned 1 time)
- Increase the size of the opening (mentioned 4 times)
- Improved design (mentioned 5 times)

3.12.3 Was Video Helpful

The last question of the post-task questionnaire asked participants if the videos were helpful in showing the participant how to collect their fingerprints with the option to select: It was helpful, it wasn't helpful, it was misleading.

All of the participants responded by selecting the option that the videos were helpful. They were also given the option to provide any comments about the videos. Two participants provided comments:

- Video A was confusing. Makes me think you need the thumb too.
- Would not have known how to do it without video even when I thought I was doing it correctly.

4 IMAGE QUALITY

4.1 General Approach

As part of another project, NIST is developing a suite of computational metrics by which to evaluate the performance of contactless fingerprint scanners. The metrics under development will be presented in detail in a later publication. However, a selected subset of image quality metrics is used in the present study to evaluate the quality of the contactless finger print captures relative to those collected using a legacy contact device.

While a number of images were collected from participants during the three phases of the present study, image quality was assessed only for the best capture of the final session. For comparison, two plain four-finger slap impressions of the right hand were collected from each subject at the end of the usability tests. The slap impressions were segmented into individual fingerprint impressions for subsequent stages of the analysis procedure as described below.

4.2 Image Registration

In order to facilitate a variety of comparisons between contactless acquisitions and those using the contact device, corresponding pairs of images were registered with one another. We anticipate eventually the use of a suitably tested automated registration scheme, but for the purposes of the present exploratory work, we employ a method that determines the affine transformation that will bring the two images into registration based on control points.

The control points are selected from a simultaneous screen display of the image pair at magnifications of 200 % or 400 %. The MATLAB® tool used enables repositioning of the magnified viewport relative to low-magnification views of each of the fingerprint images. To the extent possible, we select two or three corresponding minutiae to serve as control points.

The registration tool computes the 3 x 3 affine transformation matrix that includes a scaling factor. As we desire only rigid rotation and translation, the scaling factor is removed from the transformation before application to the image to be moved relative to that set as the "fixed" image.

In order to ensure that the transformation does not translate the "moved" image beyond the borders of the "fixed" image, we add a padding of fifty pixels to the borders of the "fixed" image. The transformation adjusts the size of the rotated/translated ("moved") image to match that of the "fixed" image. Thus, the result of the process is a pair of images that are identical in dimensions and having the fingerprint content in "best-fit" spatial registration.

4.3 Overlap of Fingerprint Areas

Two very basic observations are made in comparing contactless captures with contact derived fingerprints. First, the capture may extend beyond that of the plain impressions used for comparison in the present investigation. Second, the contactless capture provides little constraint on the position of the fingerprint at the time of capture. That is, while a slap-four may include fingers that are rotated slightly, or tipped toward the finger tips to under-sample the plain impression, the necessity to contact the capture surface limits the possible variability in both area and position on the finger of the acquired sample. Contactless devices provide much less constraint on control of the capture region. Thus, we include a measure of the overlap between contactless and contact captures. Moreover, for most comparison metrics considered here, we are mainly interested in the areas sampled in common from the friction ridge surface. Thus, we need to isolate this region in each fingerprint impression under comparison.

We define a procedure by which we can determine the relative areas of each friction ridge surface sampled by the various devices as well as isolating the fingerprint region sampled in common by two devices. We may designate the two images to be compared as I_A and I_B. Process each image as follows:

1) Perform a top-hat filter to reduce uneven illumination effects;
2) Threshold the image to yield binary results, B_A and B_B;
3) Apply a morphological “closing” operation to the binary images to remove all textural detail to yield images having the fingerprint background pixels valued zero and the pixels of the fingerprint regions valued one.
4) The areas of I_A and I_B. occupied by the fingerprint are then the sums of the all image pixels in B_A and B_B.
5) The sum of B_A and B_B forms an output image, $I_{C,}$ consisting of zero values for the background, ones for pixels of non-overlapping regions, and the value two where the fingerprints overlap.
6) Converting to zeros all pixels in $I_{C,}$ not equal to two and those equaling two to the value, one, forms another binary image, B_C representing the region in common or the overlap between the two fingerprints.

The operations above provide a measure of the region of overlap between the contactless and contact fingerprint. However, we only here have the area with respect to what? Using the entire image area as a normalizing factor would give us different results for different base image sizes. We would like to see values ranging from zero (for no overlap) to one (for complete overlap of one image with the other.) We do not expect the fingerprints to be of equal area, so we normalize by dividing the number overlapping pixels by the number of pixels in the smaller of the two fingerprints. This gives us the proportion of overlap between prints having the smallest with that having the largest areas, the value of which will range between 0.0 and 1.0. This measurement we refer to as the Normalized Area of Overlap.

For other measures, we wish to compare only the overlapping regions of the two fingerprints under comparisons, delineated as the non-zero pixels in $B_{C.}$ We use other MATLAB functions to determine the coordinates of the upper left and lower right corners of the smallest rectangle that will enclose the region of the non-zero B_C. Using these coordinates, we are able to crop the two fingerprint images under comparison to yield I'_A and I'_B, to which comparison measures are applied.

Figure 9 exhibits distributions of normalized overlap between fingerprint image pairs under comparison. Variation in overlap was observed to be largely due to variation in the region of the friction ridge surface sampled by the devices. Such variation for touchless capture results from yaw and pitch of the hand relative to the optic axis of the camera at the instant of capture. Even two contact captures of plain impressions can sample slightly different regions of the friction ridge surface, though for contact devices capturing four fingers together, such variation is limited. Device A captures a region larger than that of a typical plain impression, hence it covers the region of the Guardian plain impression almost completely in most cases. The lower medians and larger variability for Devices B and C, exemplifies one of the vulnerabilities of contactless capture. Namely, the absence of constraint on hand position can yield fingerprints with cores, that would typically be nearly centered in a contact capture, displayed sometimes to extremes or being absent completely from the recorded impression.

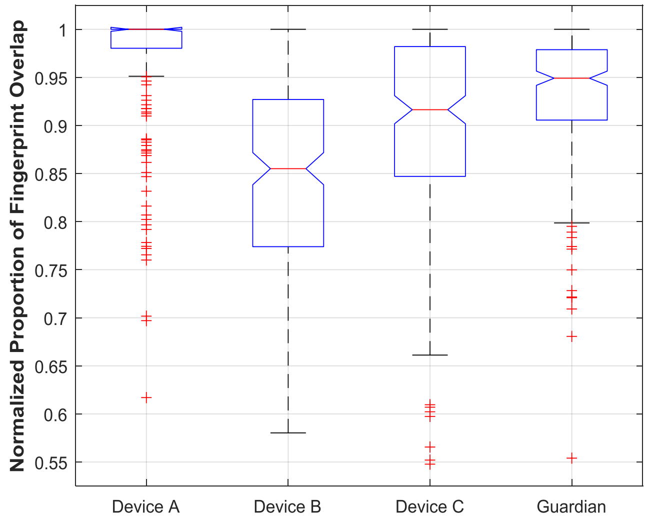

Figure 9. Overlap between contact fingerprint and corresponding contactless acquisition or between the two Guardian acquisitions.

4.3 Blind Signal-to-Noise Ratio (BSNR)

Zhang and Blum [4] describe a method for estimating the signal-to-noise ratio of images subjected to some noise or other degrading process in the absence of an original, unprocessed image for comparison. Boult [5] summarizes experiments applying the metric to images corrupted by noise, JPEG compression, and contrast (gamma) variation. The method involves analysis of the histogram of the edge intensity image, $\|\nabla I\|$, i.e. the L_2 norm of the gradient of image, I, at each pixel location. Thus, the procedure begins with the computation

$$\|\nabla I_{ij}\| = \sqrt{\left(I_{ij} - I_{i(j+1)}\right)^2 + \left(I_{ij} - I_{(i+1)j}\right)^2}, \quad i = 1...n;\ j = 1...m \tag{1}$$

The metric, Q, based on the distribution (histogram) of image gradient values is taken as the proportion of pixels of $\|\nabla I\| > 2\mu$, i.e.

$$Q = P\left(\|\nabla I\| > 2\mu\right) \tag{2}$$

where

$$\mu = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\|\nabla I_{i,j}\|}{n \cdot m} \tag{3}$$

The metric, QR, blind signal to noise ratio, is then given as

$$QR = 20\log_{10}\frac{Q}{e^{-\pi}} \tag{4}$$

The value, $e^{-\pi}$, is the minimum value for a signal consisting of Gaussian distributed noise and is used in the calculation as a base level for the metric – namely as Q approaches the minimum value for a Gaussian signal, QR approaches zero.

In the present instance, the procedure is applied to each of the cropped regions, I'_A and I'_B, common to both fingerprint images under comparison. In interpreting BSNR, one should keep in mind that it favors sharp edges and high contrast.

Distributions of BSNR for fingerprint images of the three contactless devices and of repeat captures from the Guardian FTIR sensor are shown in Figure 10. Inasmuch as this measure responsive to gradients, Device B scores highly as most of the images were binary valued and poorly defined, the edges of the segments remained sharp with this sensor. Devices A and B displayed varying degrees of high frequency noise in addition to less crisply delineated ridges, hence lower BSNR values. The Guardian controls tended toward crisp edges, but some were low contrast captures reducing the BSNR values.

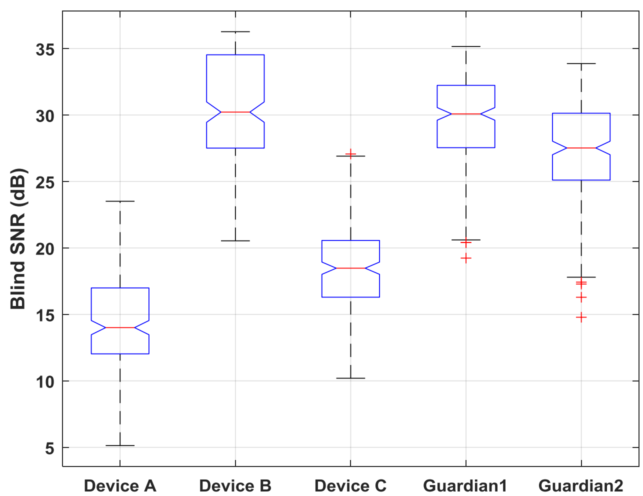

Figure 10. Blind SNR scores for fingerprint acquisitions from three contactless fingerprint devices and for each of two acquisitions using the Guardian contact device.

4.4 Frequency Spectrum Comparison

4.4.1 NIST Spectral Image Validation/Verification (SIVV) Measures

Developed initially as a method to screen fingerprint databases for non-fingerprint images, segmentation errors, or mislabeled sample rates, the Spectral Image Validation Verification (SIVV) metric [6] provides a comparatively straightforward method by which to assess the frequency structure of a fingerprint image. Pairwise display of the SIVV signals of a pair of images enables summary visualization of the effects of differences across the composition frequency spectrum of the image. As a 1-dimensional representation of a 2-dimensional Fourier spectrum, the SIVV metric applied to a fingerprint image exhibits a major peak corresponding to the frequency of the ridge spacing. Also, as shown in Figure 11, comparison of SIVV signals of two synthetic fingerprint impressions shows the difference in spectral power over various frequencies with some low-pass filtering applied to one of the fingerprint images.

The SIVV signals denoted as $\mathbf{s}_1$ and $\mathbf{s}_2$ are respectively vectors of SIVV signal values for images under comparison. The frequency samples, f, in units of cycles per pixel correspond to image pixels or Fourier transform frequencies along the length of one half of the minimum dimension of the 2D Fourier transform of the image under examination. Frequency along this dimension is scaled to the interval [0, 0.5] cycles/pixel. Note that the power value at ff = 0 is the "direct current" (DC) term, corresponding to the average intensity of the image and is used to normalize the power spectrum.

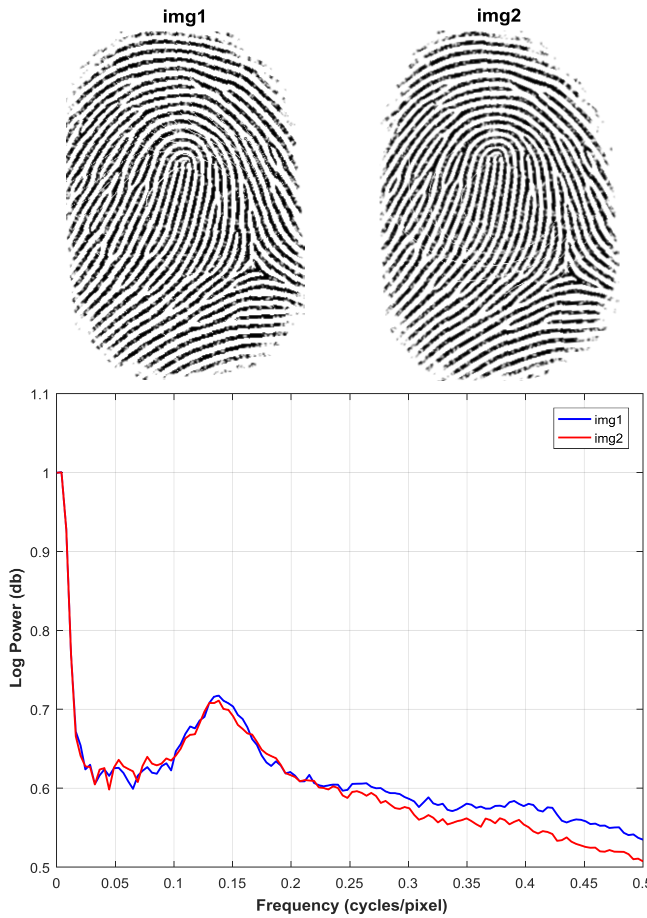

Figure 11. SIVV spectra of the two fingerprint impressions shown above. Peak location corresponds to spatial frequency of ridge pattern. Image 2 has been subjected to a small degree of low-pass filtering to reduce power in the high frequencies.

4.4.2 RMS Error of SIVV Signals

Either differences or ratios of SIVV signals can provide quantitative measures for the comparison of images methods. For the present study, we examine image differences between pairs of images, I'_A and I'_B, with respect to the Root Mean Squared Difference (RMSD) between their two SIVV signals, $\mathbf{s}_1$ and $\mathbf{s}_2$, over the entire frequency range 0 - 0.5 cycles/pixel.

$$RMSD(\mathbf{s}_1, \mathbf{s}_2) = \sqrt{\frac{\sum_{i=1}^{n} (\mathbf{s}_{1,i} - \mathbf{s}_{2,i})^2}{n}} \quad (5)$$

where $n = |\mathbf{s}_1| = |\mathbf{s}_2|$ (i.e., the lengths of the signal vectors).

The RMSD metric defined above can provide a measure of the overall difference between the SIVV spectra of images subjected to different processes or, as in the present study, fingerprint impressions acquired using different devices. In addition to global effects, the RMSD may be evaluated over smaller frequency intervals enabling the comparison of effects over frequency bands that may have particular relevance to fingerprint image quality or matching, as well as quantifying and isolating changes confined to bands that specifically impact either the machine matcher or expert examiners.

For the present purpose, we compute the RMSD for corresponding cropped images, I'_A and I'_B. Figure 12 exhibits distributions of RMSD values for comparisons of contactless captures to Guardian controls as well as for a second Guardian image to the controls. The Guardian-to-Guardian comparisons show the lowest RMSD as well as the smallest variance. Samples captured using the identical device might be expected to share frequency characteristics. Devices B and C show similar frequency comparison with controls, though considerably greater RMSD than the two contact images. Device A appears to differ considerably from the other devices with respect to this metric.

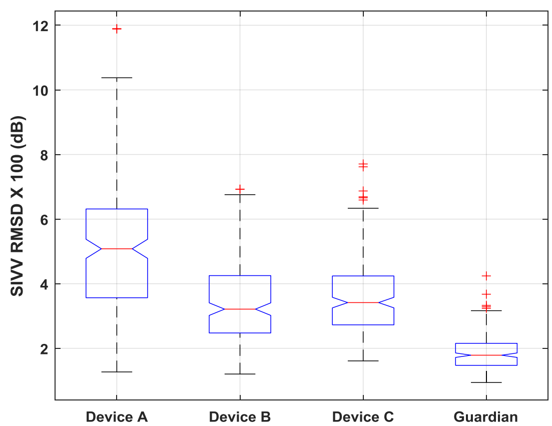

Figure 12. Root Mean Squared Difference of the spectra of contactless to contact (or contact to contact in Guardian case). Lower values are better.

4.4.3 Correlation of SIVV Signals

The RMSD measures the total deviation of point-wise comparison of the SIVV signals. The Pearson product moment correlation coefficient measures the parallelism between the two signals irrespective of the magnitude of the difference between them. Accordingly, we compute the correlation coefficient between $\mathbf{s_1}$ and $\mathbf{s_2}$ as

$$r(\mathbf{s}_1,\mathbf{s}_2)=\frac{\sum_{i=1}^{n}(\mathbf{s}_1-\bar{\mathbf{s}}_1)(\mathbf{s}_2-\bar{\mathbf{s}}_2)}{\sqrt{\sum_{i=1}^{n}(\mathbf{s}_1-\bar{\mathbf{s}}_1)^2}\sqrt{\sum_{i=}^{n}(\mathbf{s}_2-\bar{\mathbf{s}}_2)^2}} \quad (6)$$

where $\bar{\mathbf{s}}_1$ and $\bar{\mathbf{s}}_2$ are the arithmetic means of the two SIVV signal vectors.

Figure 13 exhibits distributions of SIVV signal correlation coefficients for comparison of the four devices to contact control impressions. Again, we see the best agreement between the two Guardian images, with a median value around 0.99 and a very small dispersion. While the contactless device image spectra show lower frequency signal correlation and broader dispersion; the median correlations are moderately high.

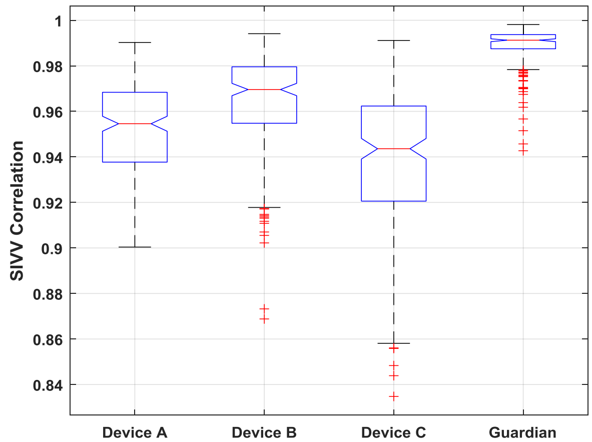

Figure 13. Correlation between spectra of corresponding contactless and contact fingerprint impressions or two impressions acquired with the Guardian contact device.

4.5 NIST Fingerprint Image Quality (NFIQ)Version 2

In 2004 NIST developed the first publicly available fingerprint quality assessment tool, NFIQ. Calibrated against fingerprint match performance, the NFIQ metric enabled evaluation of fingerprint samples relative to their relative suitability for recognition. In 2016, NIST, in collaboration with Federal Office for Information Security (BSI) and Federal Criminal Police Office (BKA) in Germany as well as research and development entities, MITRE, Fraunhofer IGD, Hochschule Darmstadt (h_da) and Secunet, issued a revision to the fingerprint image quality standard, NFIQ 2.0. NFIQ 2.0 is the basis for a revision of the Technical Report ISO/IEC 29794-4 Biometric sample quality Part 4: Finger image [5] into an international standard. Specifically, NFIQ 2.0 quality features are being formally standardized as part of ISO/IEC 29794-4 Biometric sample quality – Part 4: Finger image data [7]. NFIQ 2.0 source code serves as the reference implementation of the standard.

NFIQ2 was applied to individual images, contactless captures as well as both contact acquisitions. The metric was applied to full-sized, registered images rather than to cropped regions of overlap. It should be noted that NFIQ2 has not been calibrated for contactless fingerprint impressions. Hence, the constituent image measurements have not been adjusted relative to their contribution to recognition performance as have those acquired using legacy devices.

Figure 14 exhibits distributions of NFIQ2 scores for the three contactless devices and for each set of contact captures.

As with BSNR we note that device B appears to perform well with this metric. Once again, this is likely due to sensitivity of the NFIQ 2.0 to edge crispness, pattern clarity, and feature (minutiae) definition. The Guardian contact images follow in median score, followed by Device

A, with Device C performing rather poorly. It is notable in this regard that Device C images often exhibited blurring of ridge detail that would explain low scores on a metric emphasizing edge sharpness and low noise.

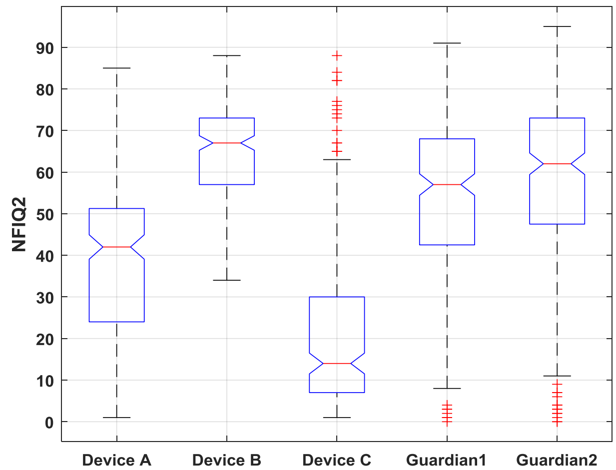

Figure 14. NFIQ 2.0 scores for acquisitions of each of 3 contactless devices and each of the two acquisitions from the Guardian contact device.

4.6 Correlation of Ridge Orientation Maps

We compare via correlation the block-wise estimates of ridge orientation. We create an orientation map of ridge orientation for each of the two overlapping regions of the registered images, I'_A and I'_B. For this we apply the method described by Thai in [10] as modified by Kovesi for a MATLAB function [11]. The method estimates the local orientation of ridges within a 7 x 7-pixel block centered on each pixel of the image being processed. The output is a map of angles in radians corresponding to the size of the input image. Thus, applying the procedure to the cropped regions of overlap, I'_A and I'_B, we get orientation maps, O_A and O_B. We then simply compute the correlation of the two orientation maps using the 2D version of equation.

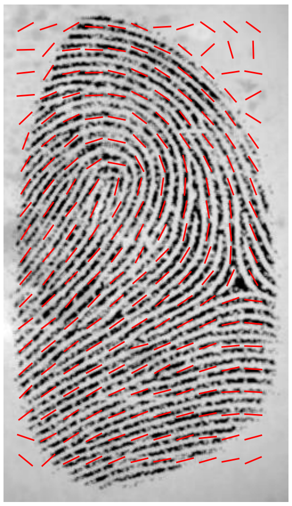

Figure 15. Synthetic fingerprint showing vector field of estimated ridge orientations.

Figure 15 provides an example of a synthetic fingerprint overlain by a graphic depiction of the vector field of local ridge orientation. This depiction is actually coarse compared to the actual array of angles which includes a value computed at every pixel location of the source image.

Figure 16 exhibits the distributions of 2D correlations of orientation maps for touchless captures to the corresponding control contact images and for comparisons of the two contact captures. The contact impressions show the highest agreement in local ridge orientation, followed by Devices A and B that show similar comparison to the contact controls.

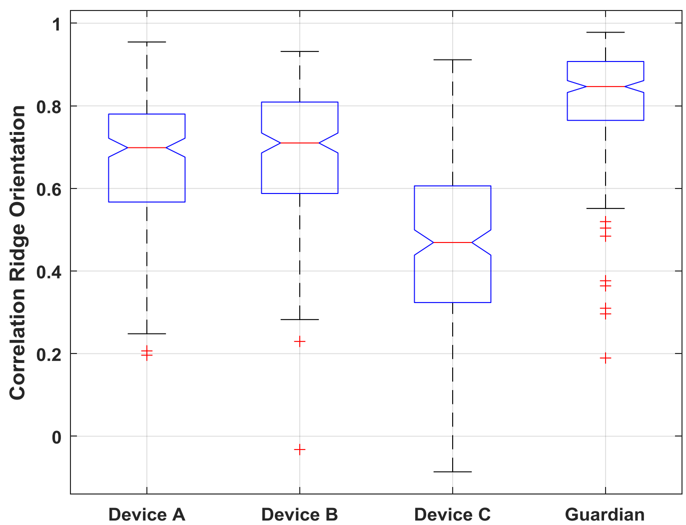

Figure 16. Distribution of correlation of ridge orientation maps estimated for overlapping regions of fingerprints under comparison, contactless devices A, B, and C against Guardian and two Guardian images to each other.

4.7 Minutiae Comparison and Matcher Similarity

Given that the cropped image regions under comparison are spatially registered to one another, it is possible to measure the distance by which corresponding minutiae are offset from one another when applying a state-of-the-art fingerprint feature detector. We had access to a proprietary software code[4] that, when provided each pair of fingerprint image samples, located the x, y coordinates and angles of minutiae of each image, identified corresponding pairs of minutiae with their respective locations and angles, and yielded a match score for the pair.

Insofar as the ultimate measure of interoperability is the capacity for fingerprints to match, we hope to assess this short of a large-scale matcher test by examining minutiae correspondence position as determined by a capable feature extractor.

The inputs to this analysis were the registered fingerprint impressions in their entirety rather than simply the overlapping, cropped regions. Hence, this was comparable to a typical mated match

[4] This code was provided to NIST under a Cooperative Research and Development Agreement (CRADA) that prohibits us from revealing the source of the code or details of its operation beyond that described in the present report.

scenario with the exception that the images were identical in dimension and the fingerprint impressions contained were spatially registered as described previously.

4.7.1 Number of Corresponding Minutiae

We first examine the number of corresponding minutiae detected with comparison between the registered device output to the mated contact control image. Distributions for each of the devices A, B, and C as well as the second Guardian contact capture are displayed in Figure . Devices A and B display similar performance with respect to both medians and variation of distributions. The control contact device shows larger numbers of detected corresponding minutiae, and the distribution of corresponding minutiae for Device C falls well below those of the other sensors.

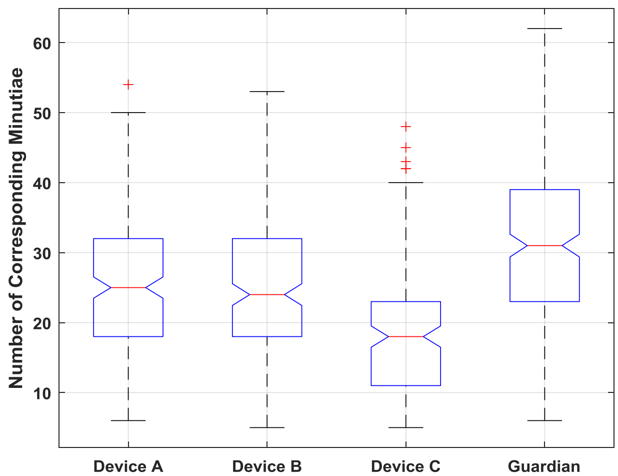

Figure 17. Numbers of corresponding minutiae for comparison of each sensor capture with contact control impressions as determined by the state-of-the-art fingerprint feature detector.

4.7.2 Mean Offset of Minutiae Placement

Given the minutiae correspondence between spatially registered images, we can compute the Euclidean distance between their placement on the common coordinate system. Distributions of these measurements are displayed in Figure 18. By far the smallest offset if found among corresponding minutiae detected in the mated contact impressions. The median value for the Guardian is significantly lower than that of the touchless devices, and the distributions shows very small variation. As with numbers of minutiae, Devices A and B show very similar median values and variation. The median values here are not significantly different. Extreme outliers, denoted by the “+” marks, are probably the result of errors in selection of control points and consequent mis-registration. Some of the images of all touchless devices and even a few of the contact images challenged reliable minutiae location.

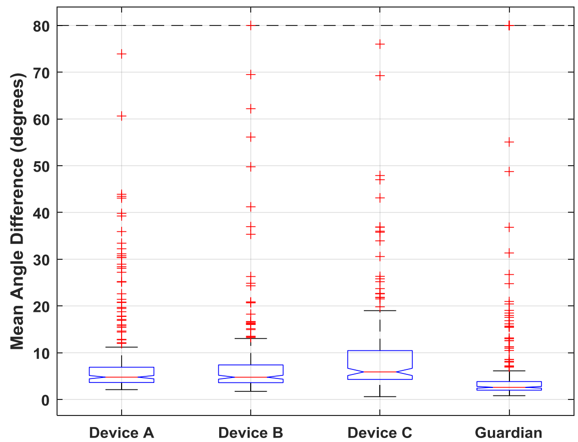

Figure 18. Distributions of mean minutiae angle differences for device captures compared with contact control captures.

4.7.3 Mean Difference of Minutiae Angle

The feature detector determines for each minutia angle as defined in the ISO/IEC standard [11]. We calculate the difference between the angles of minutiae identified as corresponding by the feature detector and plot the averages in distributions displayed in Figure 19. The pattern here is similar to that for minutiae displacement, with the contact comparisons showing the smallest median and dispersion. Again, distributions of angle deviation for Devices A and B are very similar, and Device C departs from the others.

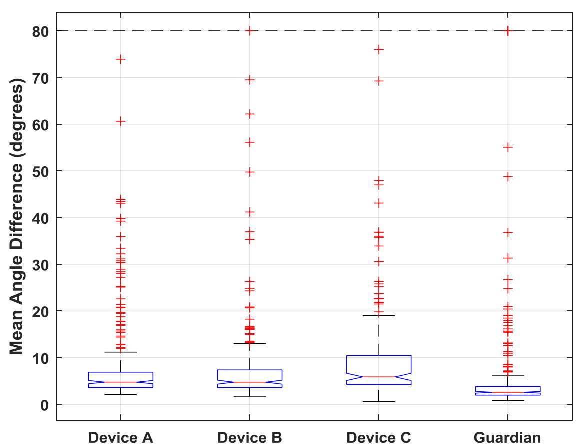

Figure 19 – Distributions of mean minutiae angle differences for device captures compared with contact control captures.

4.7.4 Match Score

Finally, we examine distributions of match scores computed between device captures and corresponding controls. This match test can be treated only as a correlation measure as a true match test examines impression relationships against a background of known non-match images. Regardless, we can still interpret the relative similarities of touchless to contact captured mates and that between the two contact device captures.

Distributions of matcher similarity scores are exhibited in Figure 20. The contact-to-contact mated comparisons shows median and most of the distribution significantly higher than any of the touchless devices in mated comparisons with contact control impressions. In spite of this, however, both Device A and Device B distributions fall significantly higher than the maximum similarity scores computed for known non-mated impressions. The non-mate (impostor) test was quite small, on the order of several hundred image pairs, but all scores were less than 100. Even Device C shows most of its score distribution above the imposter score threshold, though we suspect that in its configuration for this usability study, Device C might face greater performance challenges in a full-scale matcher test.

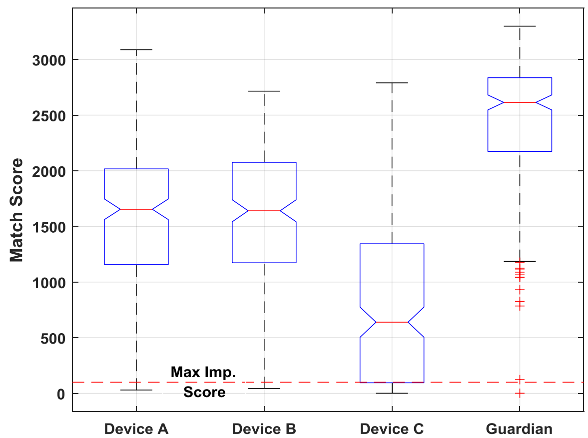

Figure 20. Distributions of matcher similarity scores of device captures and contact control impressions. The maximum score among known non-mates (impostors) is indicated by the horizontal dashed line (a score of 100).

4.8 Discussion of Quality and Interoperability Examination

We note that the foregoing considers only the final capture for each of the touchless devices. No attempt was made to examine quality or interoperability of touchless impressions captured in rounds one or two of the usability test. Thus, the results described in section 5 of this report are a reasonable sample of what performance might be expected under supervised use of the devices and not necessarily that to be expected in some unsupervised operational scenarios.

Insofar as the ultimate test of interoperability is the ability to match the touchless fingerprint impression to a legacy contact impression, we find the match score itself to be most significant. That at least two of the touchless devices exhibit scores well above an impostor baseline for mated matches to legacy device control images. Examination of minutiae number, displacement, and angle differences show their respective contribution to the pattern observed in match scores among the four devices. The correlation of ridge orientation maps shows a pattern similar to that for match scores and minutiae measurements.

As a single image metric, NFIQ2 combines a large number of measurements into a composite score. Having visually examined all of the impressions of the present study, we can assert that the elevation of Device B above even the Guardian is likely spurious. While most of the Device

B images showed sharp edges and low noise, this may have reflected the binary nature of most of the images. Even in cases where the ridge structure was severely dismembered, the segments appeared as well-defined line segments. What is surprising in this regard is that the minutiae comparison and match scores remained relatively good for this device. Also, somewhat surprising is the minutiae and match performance of Device A given that its impressions suffered from low contrast and often difficult to discern ridge structure amidst highly textured, noisy overall appearance. That we find reasonably good performance for these devices may testify to the robustness of the matcher used or perhaps any of a number of modern matchers.

An observation worthy of note is that all three of the touchless devices exhibited varying degrees of contrast (or polarity) reversal in the rendering of the ridge structure. Because of the vagaries of lighting angle across the surface, a ridge crest could either be locally brighter or darker than adjacent furrows or even in between. Often the brightest and darkest regions of a ridge are not actually coincident with ridge crest or valley floor but with opposing flanks of the ridge where one side of the ridge receives light and the opposite side is in shadow.

This polarity reversal effect is visible in the photographic representation where such is available, but is lost completely in the gray-scale or binary rendering of the photograph. Accordingly, it was not uncommon in comparing touchless prints with mates captured using the FTIR technology to find it difficult to find corresponding minutiae when looking specifically for either ridge endings or ridge bifurcations. Instead, a ridge ending in the contact exemplar sometimes did not appear similarly positioned in the touchless print. Yet the touchless print displayed a bifurcation in the corresponding position.

We found that the minutiae correlator and match software described above did not even report minutiae type, suggesting that for its purposes a ridge ending or bifurcation were considered the same – just a feature available for comparison. That type was ignored entirely probably accounts for the reasonably high match scores for the touchless sensors. This further suggests that whereas the polarity reversal problem of touchless sensors inhibits human fingerprint comparison, the problem may be overestimated in importance where machine matching is concerned.

5 DISCUSSION

The results of this study show that contactless fingerprint technology is a viable option. But with that option are a number of associated usability challenges the technology presents. These challenges will need to be addressed to ensure users can successfully capture their fingerprints.

5.1 Mental Models – Touching the Glass or the Device

A mental model is an internal representation of how something works in the real world. We use mental models to help us decide the best course of action in a given or unfamiliar situation [3]. Participants in this study were using mental models from their past experiences to predict how to capture their fingerprints with the devices.

All participants were NIST employees and had previous experience with capturing their fingerprints on a contact scanner. Fingerprint captures for NIST employment includes four-finger capture of left and right hands and left and right thumbs. So, all of the participants had experience with a traditional device that required touching a platen to capture their prints.

Participants were also aware that the devices had a camera that would capture an image of their fingerprints. Their mental models for capturing an image caused them to limit all movement. All the devices required the participant to move their hand either through or into the device. Both of these mental models led to unsuccessful attempts by the participants to capture their fingerprints.

In Round 1 of testing, participants frequently tried to touch the glass on Device A and various areas of Device B. No instructions were provided and none of the participants were successful using these devices during the initial round of testing. The design of Device C had limited areas that participants could try to touch, although participants did attempt to touch the lid on the opening of Device C.

5.2 Ready Status, Feedback, and Hand Placement

Another usability challenge for participants was the lack of status (i.e., was the device ready) and feedback (i.e., were prints successfully captured). Participants were not used to having to move in order for a camera to work because typically people hold still. Two of the devices required the participant move their hand to be successful, the antithesis to user's expectations. None of the devices signaled that the device was ready to collect the participant's fingerprints nor did they signal the participant that the capture was successful. None of the devices provided instructions to the user about what the user should do to collect prints, correct hand placement, or which hand is expected.

5.2.1 Ready Status

None of the devices indicated to participants that the device was ready to use. Device A had a green light that indicated the device was on and functioning. Participants assumed that light meant the device was turned on. Device B also had a green lighted area and participants again assumed that meant the device was on. Device C was black until the participant stuck their fingers or thumb into the device and then the camera would flash. Participants assumed that meant the device had captured an image of their fingerprints. But participants had to make assumptions to how the device worked in order to determine whether the device was ready to capture prints.

5.2.2 Feedback

None of the devices provided feedback to participants as to the success or failure of their fingerprint capture. Device A's camera would flash and participants assumed that their fingerprints were captured, but they were unsure if that meant it was a successful capture. Device B had a lighted ring around the capture area and it would flash and ding if the device captured an image of the participant's hand. Again, participants were unaware the device successfully captured their fingerprints. Because the camera in Device C was housed in a box, it was difficult for participants to see the camera flash when they put their fingers into the device. If the participants bent down to look inside the opening of Device C, they could see the camera flash but the device did not provide information about successful or failed fingerprint captures.

5.2.3 Hand Placement

All participants were familiar with having their fingerprints captured on the Guardian device. The device requires the user to touch the platen to capture their fingerprints. Understandably, as a result, the participants also wanted to touch the touchless devices somewhere to capture their prints. The Guardian device requires users to touch the platen, but not move their hand to capture their prints. Two of the touchless devices required participants to move their hand in some motion to capture their prints successfully.

During the first round of testing, all but one of the participants tried to touch the glass on Device A. The one participant who did not try to touch the glass had previous experience with a similar device. In general, participants did not understand how or where to place their hands.

In the first round of testing, none of the participants knew where or how to place their hands to have Device B capture their fingerprints. Many of them touched various areas on the device and waited to see what would happen. Some of the participants who held their hand in the opening, saw the lighted area flash and ding, and as a result thought they had successfully captured their fingerprints. They did not realize that the flash and ding only signaled that the device had detected their hand.

Device C was a small box with an opening limiting the number of hand positions participants could attempt to capture their fingerprints. Even though these options were limited, 10 participants touched the lid to capture their fingerprints during the first round of testing. The only feedback was a quick flash when the participants stuck their hand into the opening.

5.3 Usable Touchless Devices

Participants had issues trying to capture their fingerprints successfully with the touchless scanners. They were unsure when the device was ready to capture their prints, how to capture their fingerprints, and whether they were successful in their efforts. For these touchless devices to assist people to capture their prints successfully the devices need to clearly indicate:

- Status of the device, i.e., the device is ready to collect prints
- Provide instructions including what the user should do to collect prints, hand placement, and which hand is expected.
- Appropriate hand or finger placement
- Feedback about successful or failed print capture
- How to recover or what to do if capture failed

6 CONCLUSION

Participant’s mental model of the fingerprinting capture process includes touching the surface of the fingerprint scanner and their mental models for capturing an image requires them to limit movement. During the usability test of the touchless fingerprint scanners, it was clear that without instructions, participants would attempt to touch the surface of the scanner to collect their fingerprints. Touching the device left latent prints on the scanner and sometimes the scanner would have to be reset because touching the device caused it to malfunction.

Touchless fingerprint scanners require the participant to perform some type of movement and not touch any surfaces to capture a print. The resulting behaviors may have implications for DHS who plans to continue to develop and use contactless fingerprint technology. It is to be expected that it will likely to take longer times for people to successfully collect their fingerprints while they are getting accustomed to contactless scanners. This time will have to be accounted for due to its impact on throughput, and may result in longer lines at entry points. An effort must be made to provide clear instructions in the use of contactless scanners to counteract these possible delays.

With respect to image quality, we note that with regard to conventional notions of fingerprint image quality such as pattern clarity, contrast, gray-scale distribution, and noise touchless images tend to diverge from those acquired via legacy technologies. Hence, conventional fingerprint image quality specifications cannot be applied to touchless fingerprints. However, the minutiae correspondence and matcher analysis applied to the small sample of fingerprints considered in the present investigation suggest that touchless prints can be interoperable with legacy captures with respect to machine matching. Human comparison of touchless fingerprints to legacy images may be complicated by the image quality differences, including polarity reversals due to vagaries of illumination, but a capable machine matcher is able to correlate fingerprint features of mated contactless captures and legacy impressions sufficiently to generate match scores well above those for non-mated comparisons. Accordingly, verification of touchless prints against legacy databases appears quite feasible. Interoperability in one-to-many comparison remains uncertain as such testing was beyond the scope of the present investigation.

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APPENDIX A – Information Sheet

Project Title: "Contactless Fingerprint Capture"

NIST Principal Investigators:
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Co-Principle Investigator: Brian Stanton, Phone (301)975-2103, Email: brian.stanton@nist.gov

Research Description
This study is being performed to determine the usability of three fingerprint scanners to improve the fingerprint collection procedures. The research is funded by the Department of Homeland Security (DHS) and conducted by the National Institute of Standards and Technology (NIST).

Requirements for Participation
In order to participate in the research project, you must be at least 18 years old and a Federal employee with your management's approval to participate in this research as part of your official duties.

Study Procedure
You will be asked to complete a short pre-task questionnaire to provide your age category, gender, handedness, height, country of origin, and experience with fingerprint scanners. After the pre-task questionnaire, you will be asked to leave three sets of fingerprints using each of three fingerprint collection devices; you will do this three times using three different sets of instructions for the fingerprint collection. Each fingerprint collection will consist of capturing the four fingers of your right hand. Following the fingerprint collection on each device, you will complete a short questionnaire to record your experience during the collection. A video recording of just your right hand will be taken while you are using each of the three scanners. After you have completed the three rounds of fingerprint captures, you will complete a post-task questionnaire to provide your overall experience with the three fingerprint scanners. All of the fingerprints, questionnaire data, video, and written notes by the researchers will be recorded without identifiers. This process should take you no more than 30 minutes.

In total, we expect to have no more than 200 participants complete the experiment.

Confidentiality
You will be assigned a participant number that will be used for all data in this project. Your identity will be protected to the extent permitted by law, including the Freedom of Information Act. The Office for Human Research Protections (OHRP) of the U.S. Department of Health and Human Services, appropriate NIST researchers and other appropriate Federal employees may review the records of this study. The study data will be used only by NIST researchers to provide guidance on fingerprint collection procedures. All of the fingerprints, questionnaire data, video, and written observation notes by the researchers will be recorded without identifiers. All of the

data will only be recorded by a number, and will not be linked back to an individual in any way. NIST will not keep a list that links your participant number to your name or other identifying information. In responding to the freeform questions in the questionnaire, do not include any personally identifiable information in your responses.

Voluntary Participation
Your participation is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You are free to withdraw from the study at any time during the experiment, without penalty or loss of benefits to which you are otherwise entitled. If you decline to answer a question the session will continue. If you withdraw from the study, your data will be removed from the study.

NIST Approval ____________________________ NIST Case # ___________

Potential Risks and Benefits
The risks during performance of the study activities are minimal and not greater than those ordinarily encountered in daily life or having your fingerprints captured. You will not benefit directly by participating in the study. The long-term benefits of this study to society are expected to be improved fingerprint collection procedures.

Contact Information
For questions regarding this study, please contact Mary Theofanos at301)975-5889, mary.theofanos@nist.gov, or Brian Stanton at 301-975-2103, bstanton@nist.gov. For questions regarding your rights as a human subject, please contact Anne Andrews, Director, NIST Huma Subjects Protection Office, at (301)975-5445 or anne.andrews@nist.gov. Any research-related injury during the study should be reported to Mary Theofanos at (301)975-5899, mary.theofanos@nist.gov, or Brian Stanton at (301)975-2103, brian.stanton@nist.gov.

Summary
Remember, you should only participate if you are a Federal employee with your management's approval to participate in this research as a part of your official duties; you are at least 18 years of age; and you have also spoken to one of the NIST researchers, Mary Theofanos or Brian Stanton, who answers your questions you had about this project.

DO NOT SIGN THIS INFORMATION SHEET,
PLEASE KEEP IT FOR YOUR RECORDS

APPENDIX B – Demographic Questionnaire

1. What is your age category:
   ☐ 18 – 20
   ☐ 21 – 25
   ☐ 26 – 30
   ☐ 31 – 35
   ☐ 36 – 40
   ☐ 41 – 45
   ☐ 46 – 50
   ☐ 51 – 55
   ☐ 56 – 60
   ☐ 61 – 65
   ☐ 66 – 70
   ☐ 71 +

2. What gender to you identify with (please select one)?
   ☐ Male
   ☐ Female
   ☐ Prefer not to answer

3. Which is your dominant hand (please select one)?
   ☐ Right
   ☐ Left
   ☐ Ambidextrous

4. What is your country of origin? ___________________________

Scanner Experience

5. Have you used any fingerprint scanners before (excluding any smartphone fingerprint scanners)?
   ☐ Yes ☐ No

   IF YES, how many times have you interacted with a fingerprint scanner?
   Please select the number of times:
   ☐ 1 ☐ 2 ☐ 3 ☐4 or more

6. Do you use or have you used a fingerprint scan feature on your smart phone?
   ☐ Yes ☐ No

   IF YES, which smart phone(s) have you used (for example, IPhone 5s)?

APPENDIX C: Post-Task Questionnaire

1. Do you think the fingerprint scanner was:
    __ Too fast
    __ Too slow
    __ Took the appropriate amount of time

2. Could you tell if the scanner was ready to accept your fingerprint?
    __ No, I couldn’t tell
    __ Yes, I could tell
    __ I was unsure

3. Could you tell whether your fingerprint was successfully captured?
    __ No, I couldn’t tell
    __ Yes, I could tell
    __ I was unsure

4. Without instructions I knew what to do to capture my fingerprints using the device.
    __ Strongly agree __ Agree __ Disagree __Strongly disagree

5. How would you describe your experience with this device (for each device)?

Video Questions
You watched a video for each device that demonstrated how to collect your fingerprints.

1. Rate how strongly you agree or disagree with the following statement:
    I could understand what to do after watching the video?

    __ Strongly disagree __ Disagree __ Agree __Strongly Agree

2. Was the video clear about how to collect your fingerprints?
    __ The video was not clear
    __ The video was clear
    __ I am unsure

(note: Video Questions were only asked round 2 of testing)

Appendix D: Post-Session Satisfaction Questionnaire

1. Please rank the fingerprint scanners in order of how easy they were to use with **1** being the easiest to use to **3** being the most difficult to use.
   __ Device A
   __ Device B
   __ Device C

2. Why did you rank the fingerprint scanner in that order?

3. Which fingerprint scanner did you prefer (**select one**)?
   __ Device A
   __ Device B
   __ Device C

4. Why do you prefer this fingerprint scanner?

5. Do you think any improvements are needed for:

   Device A
   __ No
   __ Yes

   What improvements?

   Device B
   __ No
   __ Yes

   What improvements?

   Device C
   __ No
   __ Yes

   What improvements?

Video

Was the video helpful in showing you how to collect the fingerprints?

For Device A:

__ It wasn't helpful
__ It was helpful
__ It was misleading

For Device B:

__ It wasn't helpful
__ It was helpful
__ It was misleading

For Device C:

__ It wasn't helpful
__ It was helpful
__ It was misleading