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Closed Loop Feedback Mechanism Effect Pilot Investigation on Manual Assembly Time and Process Variation

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Abstract

Increasing customer demand for individualized and cost-effective products within shorter production times is reshaping the manufacturing and production environment. Human workers and machines must be able to react to changes with increased flexibility and efficiency. To meet these needs, the tools and products of modern assembly have continually updated and changed, but much work remains to incorporate the natural intelligence of an assembly worker more deeply into future assembly system information flow, both to and from the worker (feedback loop). This work presents a pilot lab evaluation of varied real-time feedback mechanisms for human workers on manual assembly processes to understand better how the method of the information feedback loop to the assembly associate affects their assembly time, variance, and accuracy as well as their perceived acceptance of each mechanism for information feedback. Lego building block models were used as the assembly product to build while wearing a wireless feedback mechanism device. The device incorporated LED lights, vibration, a text screen, and an image screen to provide feedback to the worker. All feedback was provided by an administrator who was able to send commands to the respective feedback methods as needed. Early conclusions in the pilot show a difference in the assembly time depending on both the feedback mechanism used and the complexity of the assembled model. Future work will include expanding the number of participants per test case and increasing the number and types of feedback provided to include non-wearable types such as stationary monitors and sound.

Keywords: Human-machine interaction; Human-centered manufacturing systems; Manual assembly; Cyber-human systems

1. Introduction

Advancements in technology and communications are making substantial ubiquitous computing a reality in the consumer market with the computing power of a modern consumer's cell phone quickly approaching the power of traditional stationary computing systems.

Similar to the motivation provided by gamification of fitness tracker metrics on consumers' efforts to understand and improve their health, a push towards gamification of real-time human feedback during manual manufacturing processes holds promise to increase the wearers understanding of the individual impact on final process quality through alerts to incorrect or incomplete tasks at the time of work and providing a readily available avenue towards daily improvements [1]. Also, collected metrics of individual training effectiveness and level by comparing worker task success rates with simulation and situated learning can improve virtual modeling (i.e., the digital factory twin) toward optimizing production planning through a deeper understanding of individualized workforce performance distributions and predicting the effects of process changes/variations due to human behavior [1–3]. Such approaches drive the knowledge of the humans' role in and influence on product quality [4–7].

High levels of manual value-added content principally describe the unique nature of automotive assembly, which assembles a high-value high-complexity product. Increasing consumer option content increases product complexity and assembly complexity. Design for Assembly principles diminish the impact of consumer option content on assembly complexity, but above a specific threshold limit, continuous

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adaptation becomes impractical [8]. Previous literature has shown that manual assembly human error (defects which are not always obvious or straightforward to detect) tend to make up to 40% of total defects [9–11]. Organizational and technological structures have historically been enhanced to address this issue, but the role of the human worker within these systems has changed very little since the days of the first automobiles, though humans remain a significant player in their production [12–15]. Non-obvious human errors are challenging to control, and the continual emergence of new defect sources such as increased self-inspection and instructions that alternate attention between interpretive and value-adding activities have been shown to have a negative impact on assembly performance that can result in costly defects [10,16].

With the automotive manufacturing industry embracing the push toward future Cyber-Physical Systems and Industry 4.0, which have traditionally tended to displace the human worker in favor of less flexible automated systems, automotive assembly has remained somewhat anomalous in the sense of increasing the number of assembly associates since current automation cannot yet handle the continually growing variety and complexity in vehicles. Examples of this tendency come from a variety of manufacturers such as BMW AG, Tesla, Mercedes, and Toyota [17,18]. More humans in the manufacturing environment highlight the need for and potential influence of worker improvement programs which harness the flexibility and natural intelligence of the associate to learn from past mistakes and be guided towards higher quality work and enable them to not only make better decisions and understand their assembly processes deeper but also to motivate their active participation in quality.

A literature review of different forms of assembly instructions, previous Legos studies, and methods in process planning provided a framework for this Lego study. The experimental set-up used the lower and roof subassemblies of a Lego car and pickup truck models that were commercially available. The collected data of assembly times were evaluated by mean, standard deviation, and statistical significance to examine the relationship between feedback mechanism type and assembly performance.

2. Background

2.1. Assembly Instructions

Assembly instructions take many forms and depend heavily on the specific application and environment. Much work has been presented describing optimal methods of the presentation of work instructions and the types and amount of information that should be provided. Agrawala *et al.* presented a set of design guidelines based on cognitive psychology on how to create visual assembly instructions [19]. Through an examination of the hierarchy and grouping of parts, operations, structural diagrams, orientation and visibility of the product, the planning of a sequence of assembly operations versus the method of presenting the actions in the instructions was made.

Watson *et al.* assessed the presentation of animated assembly instructions by assembling a central gear assembly [8]. The tested instructions were text-based, picture-based, and animation-based. Volunteers for the work were divided into three groups and tasked to build one product five times. The animation was shown to have a significant positive initial impact; however, over time, the effect was minimized as the participants learned the assembly. This finding is specifically relevant to the current work as it demonstrates that differences do come from the instruction type and could similarly be seen in the method of feedback instruction.

Analogous to the animation medium presented by Watson *et al.,* researchers are developing augmented reality assembly instructions, such as in the aerospace industry. AIRBUS Military and their use of the MOON (asseMbly Oriented authOring augmeNted reality) system is one example of augmented reality work instructions [20]. The work instructions were generated from 3D information defined in an industrial digital mock-up of the aircraft and developed for an electrical harness routing in the frame of an aircraft. The difficulty was found in the interpretation of displayed information and the depiction of complex processes.

2.2. Assembly Time

Assembly cycle time is continuously reworked to determine the optimal time for building a product. Different methods have been introduced for calculating assembly time. Boothroyd and Dewhurst developed a commonly used method at UMA in 1983 [21]. This method utilized a series of worksheets based on handling and insertion assembly time data for calculating different assembly operations. The technique involved examining the part size, part weight, part resistance, part features, among others. Based on the answers to these questions, a time was associated with the operation. Overall product assembly time was then determined, and unnecessary parts were identified and removed from the assembly process.

However, associated with the process was a certain degree of subjectivity that can create a wide range of assembly times for a single assembly product. Namouz *et al.* employed the Boothroyd and Dewhurst method on a pen assembly to identify potential subjectivity in the technique [22]. They examined the need for all the information provided in the tables and the possibility of reducing the number of subjective questions. Namouz et al. eventually established an order of three different levels of subjective questions. By eliminating the first level of subjectivity from the method, reasonable and comparable assembly times were determined. More importantly, the possibility of more variation due to the subjective questions was reduced.

Owensby *et al.* compared a method to the Boothroyd and Dewey Assembly Time Method [23]. A connective-complexity method was employed to calculate the complexity of the part connections within an assembly and gather assembly time data. The results from the study indicated there was a 50% time difference from the Boothroyd method. Although the time was determined to be inaccurate, another area of potential research was to identify why the drastic difference in time occurred. Interesting to note, the Owensby's method had zero subjective questions, and a far fewer set of questions in general, making implementation easier as compared to the 49 questions employed by the Boothroyd and Dewhurst method.

In this study, volunteers were measured based on how fast they complete each subassembly and overall assembly with changing feedback method. The assembly time data were evaluated for statistical significance, although observation and user input was necessary for practical relevance to improve both the study design and to have results useful for production.

2.3. Previous Use of Lego Studies

Lego is a line of plastic interlocking bricks manufactured by the Lego Group in Denmark. Since its introduction in 1949, Legos have been used in a variety of different applications of theoretical studies. These studies ranged from behavioral group interactions [24], cost savings in a factory environment [25] to their use in engineering courses and simulations [26–28].

Legos are a fun classroom method to learn the basics of creativity as well as basic engineering principles of mechatronics[26]. Lemons *et al.* gave subjects a set of Legos to prototype designs and communicate their ideas on how they would open a jar [26]. The students were able to rapidly assemble and disassemble their designs, teaching rapid prototyping and aspects of engineering. Due to the popularity of Legos, the subjects had at least a certain degree of familiarity with their use. Engineer Lego and the ROBOLAB, two Lego teaching products, were tested in four different case studies that taught students graphical programming and control theory for an integrated system.

Finally, Verma *et al.* provided a comprehensive review of studies portraying and addressing lean manufacturing principles [28]. This review listed Legos as one of the critical methods of studies for the simulated shipbuilding industry. One simulation involved creating a Lego micro-factory, where four different stations for different forms of manufacturing and inspection services existed, and specific criteria, such as inventory and defects, were collected. The engineers could then make two changes before the next phase started to see if any process improvements occurred. Their reasons for using Legos were due to the familiarity of the product, the ease of variation in the design, and the commercial availability. In this study, volunteers did not have a strictly mechanical background, which may have skewed results. The Legos were easy to disassemble, providing a different model to test as well as simulating an assembly line of multiple products. Legos were easily compartmentalized into various subassemblies and easily acquired commercially.

2.4. Human-Manufacturing System Interaction

Human-automation collaboration (HAC) refers to human operators working interactively with intelligent automation systems in the same workspace without physical barriers of separation [29]. Increasing attention within manufacturing has been paid to human-automation collaboration due to the potential to assist assembly workers with large or complex processes by typically isolated industrial robots whose continued isolation does not increase production or reduce costs and which are not capable of rapid changes to meet the need of flexible manufacturing [1,2,30]. It is also shown that fully automated manufacturing systems are far less common for complex goods, and human workers remain the most flexible workforce [31,32].

Outside of manufacturing, Norton, Daniel, and Ariely coined the term the IKEA effect to describe the increase in the valuation of self-made products [33]. Through their experiments in assembling IKEA boxes, folding origami, and building Legos, they demonstrated a possible connection between the addition of labor and inducing a higher perceived valuation for the resulting product. Even if poorly made, by including the owner in labor to produce the product, the owner placed an increased value on their work when completed successfully. Along the same line, a small increase in process complexity by increasing reliance on the operator's skill and understanding of the process may also increase the perceived value of their work towards the resulting final product. Historically, automation of increasingly complex processes has pushed operators out of the equation by simplifying their role in and understanding of the process to the point where the worker may not have any technical knowledge of their process [34]. The perceived value of their labor, job satisfaction, and ownership of work is reduced, which can disengage the worker from the quality of their work [15]. More research is needed to test whether the IKEA effect occurs within manual assembly processes and motivation of the human workforce under increased levels of automation systems and distributed efforts of teams of workers.

Human-manufacturing system collaboration, also included with HAC under the more general category of cyber-human systems, follows the trend of increasing reliance on the human workforce while better accounting for the process variation that is associated with manual assembly. Such variation can take the form of defects due to operator mistakes from mental, perception, communication, coordination, intentional, and lack of speed or skill causes [10,15]. By connecting the worker with the manufacturing system, a feedback loop of information can be established, and real-time monitoring and feedback of process quality are created. The push to real-time human feedback has potential to positively reinforce training by alerting workers to incorrect or incomplete tasks at the time of work; allow novice workers to move from training island to the factory floor faster while still receiving training feedback and monitoring; increase understanding of individual training effectiveness and level by comparing worker task success rates with expected during situated learning; improving the digital twin (factory simulation) by optimizing production planning and predicting the effects of process changes/variations; and more accurately understanding the human role in assembly product quality [1–5].

3. Feedback Mechanism Methods Used

Four types of feedback mechanism methods were used and were sampled from commonly available devices at a size that enabled them to be wearable. The four feedback methods were combined into a single wrist-worn device that allowed for a single feedback method or combination of methods.

Combinations of feedback should have a higher chance of gaining the users' attention, as was found by Sklar and Sarter in their work on attention allocation [35]. A wrist-worn method was chosen as it was comfortable for users to wear, has been previously validated by existing literature for gaining worker attention, and would not hinder the worker in the tasks used in this pilot [35,36]. An administrator (human) monitored each step completed by the user and provided feedback to the user based on whether the step was completed correctly. The following section describes the different methods used for providing feedback to the user. Types of feedback methods included:

- LED lights
- Vibration motor
- Text screen
- Image screen

Not included in the pilot study was audible feedback as its use is strongly dependent on the background noise level and personal protective equipment such as earplugs required by the plant. Stationary feedback mechanisms such as display screens and Andon lights were also not included as they fell outside of the wearable technology of this initial study but are of interest for future work and comparison to the existing literature on work instruction effectiveness and design principles.

Also included is a brief description of the wrist-mounted device and the equipment used for transmitting the signal from the administrator to the volunteer.

3.1. Device Casing

The casing enclosed three different colored LEDs, a 1.5 inch OLED screen, a vibration motor, microcontroller (Teensy 3.2), and NRFL2401+ (receiver module). The 3D model of the casing is shown in Figure 1.

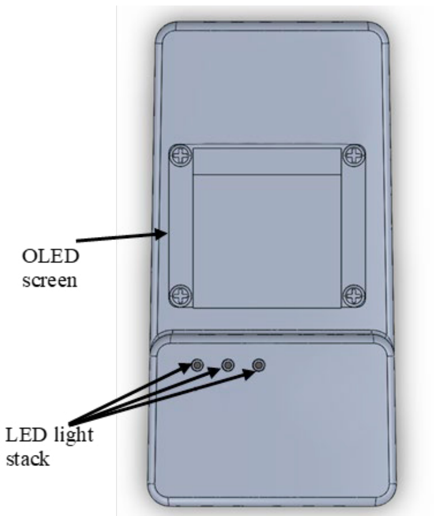

Figure 1. The casing of the wrist-worn feedback device

3.2. Control Transmitter

As mentioned prior, an administrator monitored each step of the user and sent a signal to the user from a transmitting device based on whether the step was completed successfully in a Wizard of Oz style experiment. This method typically involves the user not being aware that they are interfacing with another human while they believe the system is autonomous. In this pilot work, the users were informed that the feedback was not controlled by an autonomous system but was provided feedback as would be expected from an autonomous system. The transmitter consisted of an Arduino UNO, NRF24L01+, and Arduino Keypad. Different keys were pressed on the keypad, which activated different feedback mechanisms on the casing mounted on the user (receiver). Signals were transmitted through an NRF24L01+ transceiver module, which transmits data on a specific frequency. A similar NRF24L01+ transceiver module was placed on the user end. For the two modules to communicate with each other, they need to be on the same channel. The specifications of the NRF24L01+ module is provided in Table 1 below

Table 1. Transmitter Specifications

Specification	Value
Operating Frequency (GHz)	2.4
Nominal Current (mA)	50
Range (ft.)	50 – 200
Operating Current (mA)	250
Communication Protocol	SPI
Baud Rate	250 kbps – 2 Mbps
Channel Range	125

3.3. LED Light Stack

Three different colored LEDs were mounted on the wearable device, which was mounted on the preferred arm of the user, as shown in Figure 1. Appropriate LEDs were switched on remotely the transmitter (explained earlier) based on whether:

- The user does the step correctly – Green LED was switched on.
- The user needs to check the step – Yellow LED was switched on.
- The user does the step incorrectly – Red LED was switched on.

The brightness of the LEDs was chosen to ensure visibility to the user under all ambient lighting conditions. The specifications of the LEDs used are summarized in Table 2.

Table 2. LED Specification

Color	Green	Yellow	Red
Diameter (mm)	5	5	5
Wavelength (nm)	540	590	640
Forward Volt. (V)	3.2 – 3.8	3.0–3.4	1.8–2.2
Typical Brightness (mcd)	6000	1800	1500

3.4. Vibration Motor

A disc type vibration motor, as shown in Figure 2, was mounted on the bottom part of the casing and was glued on to the housing using epoxy to ensure that the user was able to feel the vibration. Unlike the LED light stack, the vibration motor was used only when the user made a mistake and needed to check their work. The motor was intermittently switched on and off for two seconds to alert the user

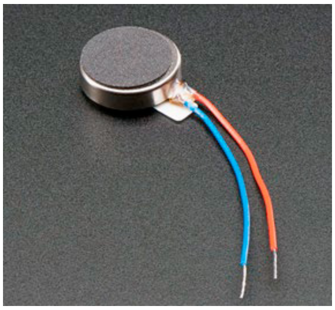

Figure 2. Vibration motor

Below are the specifications of the vibration motor.

Table 3. Vibration Motor Specification

Specification	Value
Diameter (mm)	10
Thickness (mm)	2.7
Current (mA)	100
Weight (g)	0.9

3.5. Text Screen

A 1.5-inch OLED screen was mounted on the top of the casing, as shown in Figure. Similar to the LED light stack, three different texts transmitted were as follows:

- If the user did the step correctly – "Correct" was displayed on the screen.
- If the user needed to check the step – "Please Check!" was displayed on the screen.
- If the user did the step incorrectly – "Incorrect!" was displayed on the screen.

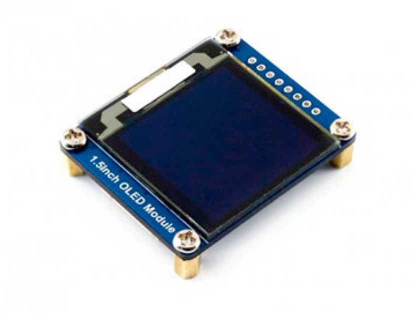

Figure 3. OLED image screen

Table 4. OLED Image Screen Specification

Driver	SSD1327
Interface	SPI/I2C
Display Color	White
Resolution	128x128
Viewing Angle (º)	>160
Operating Voltage (V)	3.3/5
Dimension (mm)	44.5x37

3.6. Image Screen

The same OLED screen used for the text screen was used for the image screen as well. Three different images, as shown in Figure 4, were displayed based on the conditions mentioned earlier. For this experiment, the SPI interface was used for communication with the microcontroller.

Figure 4. Images used as feedback

4. Methodology

Experiments completed in this work were conducted with the Clemson University Office of Research Compliance Institutional Review Board (IRB) approval, protocol number IRB2018-114. All subjects voluntarily chose to participate and were provided with a pre-experiment description of the study, any potential risks and discomforts, confidentiality, and reiteration of the voluntary nature of their participation.

A Lego 31046 set was used to conduct the experiments. The configurable products were a digger, a fast car, or a pickup truck. The product used in this Lego study is the digger shown in Figure 5, which consisted of about 200 parts in the entire assembly. Two subassemblies of the digger were used in this work.

Figure 5. Digger fully assembled

The testing environment shown in Figure 6 consisted of two shelves filled with Legos sorted into individual parts bins. Not every bin was utilized in each shelf. These bins were placed on a table within reach of the work area. Prior to the experiment beginning, the volunteer was allowed to adjust the distance of the shelves and work instructions from themselves to be within reach. Assembly instructions were presented to each volunteer in a white binder in a picture and text-based format for each step. Each user was asked to build the lower body and roof of a truck using the Lego building blocks

Figure 6. Presentation of parts to worker

Twelve students participated in testing through this pilot study. While this is a low number of participants for such a work, the intent is to use the initial pilot results to demonstrate the need for a more extensive, more in-depth investigation of manual process wearable feedback mechanisms. Each user ran through several different tests of assembly instruction. To mitigate the chance of potentially learning the subassembly, each volunteer was only allowed to complete each subassembly one time. This limitation restricted the number of tests each volunteer could complete but was done to maximize the learning that was needed to complete the assembly. Continued work will examine the longer-term use and effects of each feedback mechanism, but as previous literature has shown, it is predicted to follow the same trend of, after learning has taken place, less variation between the impacts of feedback mechanisms will exist. The lower body consisted of ten steps, and the roof consisted of eight steps. At the end of each step, the user was asked to say 'done,' and feedback was then provided depending on whether the user performed the step successfully or not. Each user used only one type of feedback mechanism, namely, light stack, vibration, text screen, and image screen for both the lower car and the roof. The time to complete the entire process of building each subassembly was recorded. The timing was started when the volunteer opened the instruction manual and was stopped after they verbally stated they were done with the entire subassembly. Mistakes and warnings were given if the volunteer made a placement mistake, selected an incorrect component, or missed a step.

Before each test, the user was briefed on the type of instructions and the organization of the parts. The text instructions follow a conventional naming system. Each part was labeled by the color, the dimensions of the part, and then the overall shape of the part. Parts with a unique variation, such as a smooth plate or an axle joint, was included in an abbreviated form after the overall shape of the part. Each part was then labeled as shown here: Color Width x Length Shape. The text instructions were written as accurately as possible to match the order of events from the original Lego picture instructions, utilizing this standard naming convention.

The picture instructions were adapted from the Lego instructions provided by the model kit. The volunteers were asked to read the instructions first and then refer to the pictures as needed. The images did not have any arrows, and volunteers were forced to rely on the text for the order for assembly in case multiple parts were added in a single step.

While the user built the product, they were timed by an administrator who sat in front of and to the side of the volunteer. The administrator recorded the time to complete each separate subassembly. Each part was then disassembled and set up for the next test. The two subassemblies tested for the digger were the lower body and roof, as seen below.

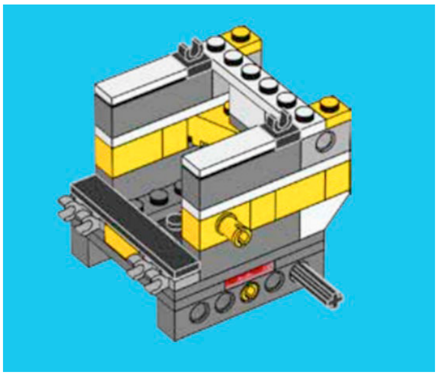

Figure 7. Digger lower body subassembly

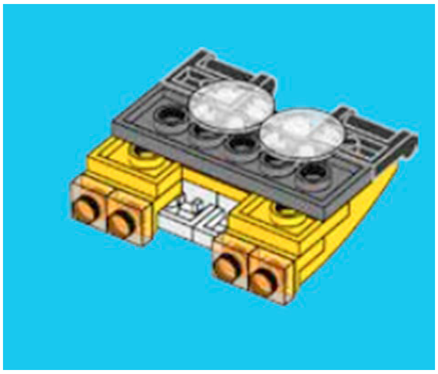

Figure 8. Digger roof subassembly

All the volunteers were given the same subassemblies but with a different feedback mechanism. It was ensured that the administrator thoroughly understood each step to provide accurate feedback at the end of each step. The volunteers were not told which subassembly they were making until just before their start. Also, on each page, there were only instructions provided for one step. Figure 7 and Figure 8 show the lower body and roof of the digger subassembly. These were chosen as they utilized different parts compared to each other and varied in the complexity of instructions required to complete.

Each volunteer participated in two experiments and completed each subassembly only one time. Each test was preceded by discussing the nature of the experiment, potential risks or discomforts, data confidentiality, and reiterating the voluntary nature of their participation in this work. The volunteer was provided an overview of the work area and was allowed to adjust the distance of the work instruction folder and shelf locations to fit their needs comfortably. Each was also allowed time to familiarize themselves with the naming convention, the layout of the shelving, and a second instruction set that was similar to the one to be used but was for a different Lego model. Finally, each participant was asked if they had any additional questions or required clarifications prior to the experiment beginning.

The experiment was begun when the administrator verbally instructed the volunteer to start, and they were now allowed to open the instructions. The timing of the experiment was begun when the instruction book was opened. The volunteer was allowed to complete each step at their own pace. After completing each step, the volunteer verbally said done, and the relevant feedback was provided by the administrator through the worn device immediately. The volunteer then moved to the next step and repeated until completion of the subassembly. Upon speaking the final done, a final instance of feedback was provided, and the timer was stopped as long as no mistake was made. The same method was completed for the second subassembly.

Upon completing the tests, the volunteers were thanked for their participation and asked a series of short questions based on the feedback mechanism used through an online survey form. The questions included how they rated each of the feedback mechanisms using a 1-10 scale with 10 being the best, preference on the location/comfortability of the wrist device, could make observations of how they felt throughout the test process and were asked if they had any remaining questions or concerns regarding the testing.

5. Results and Discussion

The mean time to complete the lower body, inclusive of all types of feedback mechanisms, was 7 minutes and 15 seconds. Table 5 shows the mean and standard deviation for all types of feedback mechanisms.

Table 5. Summary of timing results (mean and standard deviation of completion time in minutes)

Type of Feedback	Mean (Lower)	Std Dev (Lower)	Mean (Roof)	Std Dev (Roof)
LED Light Stack	5:43	2:03	4:08	2:55
Vibration Motor	9:53	1:18	6:27	1:35
Text Screen	6:50	3:00	5:33	2:16
Image Screen	6:36	0:48	6:02	0:44

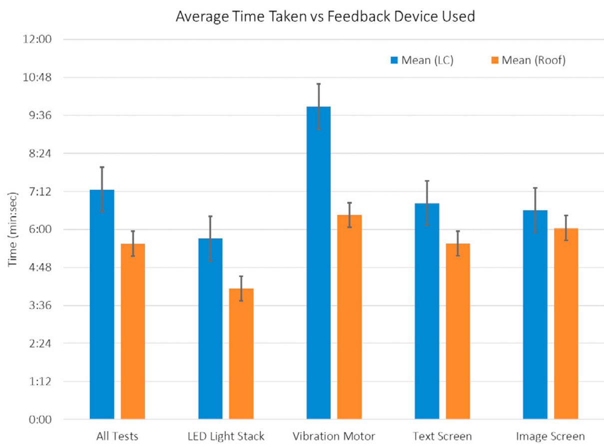

Figure 9. The average time taken vs. feedback method

From Figure 9, one can see that the lowest average time was seen in the light stack feedback mechanism in both subassemblies. This could be attributed to the bright LEDs, helping the user perceive the information instantaneously. Also, the lights chosen are very familiar in daily life, which makes it easier for the user to understand. It is also notable that while the image screen ranked second and third for average assembly time, the variation in assembly time was significantly lower than the other methods presented.

Figure 10 plots the errors made by the volunteers during testing that was recorded by the test administrator. It can be observed that the devices ranked in order from the least number of mistakes were LED lights, image screen, vibration motor, and text screen. However, care should be taken with this result as the cause of each error may not be related directly to the type of feedback mechanism as the error type/cause was not recorded. Increasing the sample size and documenting the type of assembly error during testing of each condition would help to draw further conclusions. The error rate was included in this work to provide an early representation of the potential for different types of feedback mechanism to affect the resulting error rate of a manual assembly process similar to previous literature that has investigated the method of instruction delivery with the process error rate.

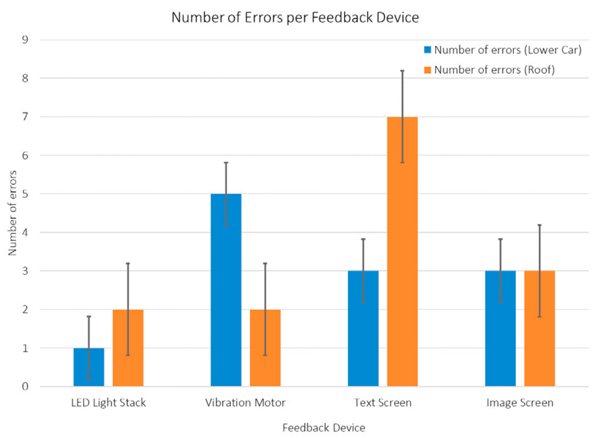

Figure 10. Number of errors made by the worker vs. feedback method

Another volunteer variable is the Lego experience level. Those with less Lego experience typically had a longer assembly time, while those with more experience had a shorter assembly time. An offset was the unfamiliarity across the board with the instructions and feedback mechanism, the tested variables. To some volunteers, understanding the picture and naming convention of the part bins was challenging. Continued work should seek to include such variations by collecting additional data to provide a complete picture of the test result variation.

5.1. Post-experiment questionnaire

All users who participated were asked to complete an online post-experiment feedback questionnaire related to the feedback method that they used. Each feedback method had at least three volunteers complete both assemblies. The output from each question was either short answer or on a scale from 1 to 10, with 10 being the highest positive response. Overall, the respondents agreed that sufficient time and information was provided to familiarize themselves with the wrist device before testing. Two of the respondents felt that the device would have been more comfortable further up on the forearm rather than on the wrist and overall, the device received a 6.4 out of 10 for the weight and size and 7.1 for shape being perceived as comfortable for the duration of the testing which lasted approximately 20 minutes per person.

Overall recommendation feedback from the workers included:

- Changing the strap design so that the user could don the device themselves
- The wrist device could have been made smaller and lighter for smaller wrists

For the LED light stack feedback, most users felt that the lights were bright enough to capture their attention and that the light was lit for a reasonable amount of time. Two users felt that a single LED should have been used rather than three, and one user wanted the LEDs to flash rather than be static lit. The average rating for the perceived helpfulness of the LEDs as a feedback method was 3.7 out of 5.

Vibration feedback was rated as not distracting and strong enough to feel through the device casing. All users showed a preference for pulsing vibratory feedback compared to the continuous used in this testing. Users thought that the time for which the device was vibrating was too long and should be shortened. Previous literature has used pulses of vibration as short as 200 milliseconds long with success in conveying information to the user in a small wrist-centered design [35–37].

Users of the text screen feedback responded that the screen size, brightness, resolution, and font were comfortable and that the amount of information provided in the text was acceptable. Some users suggested changing the color of the text based on the feedback being offered, such as red text for an error and green text for the positive feedback. Also suggested was the addition of a timer to the screen to show how much time had passed since the start of the task.

Similar to the text screen feedback, the image screen users were satisfied overall with the screen size, brightness, and resolution. Users felt that the image feedback would have been improved if a flashing image rather than a static image was used to attract their attention better.

6. Conclusion

Presented in this work is a pilot evaluation of the feedback mechanisms common to wearable devices and which might be used in future wearable devices for manual assembly processes. A wearable wireless real-time feedback system was tested that allowed four types of feedback mechanisms to be used by volunteers and evaluated based on average assembly completion time, variability, and user preference. Early conclusions point toward that the LED lights demonstrated the lowest assembly time while the image screen had the smallest standard deviation in assembly times tested. Feedback from the post-experiment questionnaire indicated an overall affirmative acceptance of the feedback mechanism device and for each method tested. It also indicated improvement potential in the form of tuning the various feedback mechanisms in the length of time the information is provided, static vs. animated, and potential additional information to include.

Future work for expanding this pilot includes expanding the number of volunteers and level of pre-experiment data collected to a point where significant statistical evidence can be drawn to provide more confidence in the resulting conclusions of feedback mechanism effect, evaluating the time effect of device usage or does user preference change depending on how long the particular feedback mechanism is used for as previous literature has shown the trend of after learning taking place, less variation between the impact of feedback mechanisms will exist, documenting the type of errors made throughout testing, and addressing the response for each feedback mechanism type provided by the pilot volunteers.

7. References

[1] Krugh M, Mears L. A complementary Cyber-Human Systems framework for Industry 4.0 Cyber-Physical Systems. Manuf Lett 2018;15:89–92. doi:10.1016/j.mfglet.2018.01.003.

[2] Lee J, Bagheri B, Kao H-A. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manuf Lett 2015;3:18–23. doi:10.1016/j.mfglet.2014.12.001.

[3] Erol S, Jäger A, Hold P, Ott K, Sihn W. Tangible Industry 4.0: A Scenario-Based Approach to Learning for the Future of Production. Procedia CIRP 2016;54:13–8. doi:10.1016/j.procir.2016.03.162.

[4] Webel S, Bockholt U, Engelke T, Gavish N, Olbrich M, Preusche C. An augmented reality training platform for assembly and maintenance skills. Rob Auton Syst 2013;61:398–403. doi:10.1016/j.robot.2012.09.013.

[5] Ward JA, Lukowicz P, Troster G, Starner TE. Activity Recognition of Assembly Tasks Using Body-Worn Microphones and Accelerometers. IEEE Trans Pattern Anal Mach Intell 2006;28:1553–67. doi:10.1109/TPAMI.2006.197.

[6] Antani KR. A Study of the Effects of Manufacturing Complexity on Product Quality in Mixed-Model Automotive Assembly. Clemson University, 2014.

[7] Krugh M, McGee E, McGee S, Mears L, Ivanco A, Podd KC, et al. Measurement of Operator-machine Interaction on a Chaku-chaku Assembly Line. Procedia Manuf., vol. 10, 2017, p. 123–35. doi:10.1016/j.promfg.2017.07.039.

[8] Watson G, Butterfield J, Curran R, Craig C. Do dynamic work instructions provide an advantage over static instructions in a small scale assembly task? Learn Instr 2010;20:84–93. doi:10.1016/j.learninstruc.2009.05.001.

[9] Su Q, Liu L, Whitney DE. A systematic study of the prediction model for operator-induced assembly defects based on assembly complexity factors. IEEE Trans Syst Man, Cybern Part ASystems Humans 2010;40:107–20. doi:10.1109/TSMCA.2009.2033030.

[10] Shibata H. Global Assembly Quality Methodology: A New Method for Evaluating Assembly Complexities in Globally Distributed Manufacturing. Stanford Univ., 2002.

[11] Vineyard M. Failure rate distributions for flexible manufacturing systems: An empirical study. Eur J Oper Res 1999;116:139–55. doi:10.1016/S0377-2217(98)00096-4.

[12] Townsend V, Urbanic J. A Case Study Measuring the Impact of a Participatory Design Intervention on System Complexity and Cycle Time in an Assemble-to-Order System. 43rd Proc North Am Manuf Res Inst SME 2015:1–12.

[13] Nee AYC, Ong SK, Chryssolouris G, Mourtzis D. Augmented reality applications in design and manufacturing. CIRP Ann - Manuf Technol 2012;61:657–79. doi:10.1016/j.cirp.2012.05.010.

[14] Wang L, Yang X. Assembly operator training and process planning via virtual systems. Int J Sustain Eng 2011;4:57–67. doi:10.1080/19397038.2010.542835.

[15] Bubb H. Human reliability: A key to improved quality in manufacturing. Hum Factors Ergon Manuf 2005;15:353–68. doi:10.1002/hfm.20032.

[16] Wang Q, Sowden M, Mileham AR. Modeling human performance within an automotive engine assembly line. Int J Adv Manuf Technol 2013;68:141–8. doi:10.1007/s00170-012-4714-y.

[17] Behrmann E, Rauwald C. Mercedes Boots Robots From the Production Line. Bloom Technol 2016:1. https://www.bloomberg.com/news/articles/2016-02-25/why-mercedes-is-halting-robots-reign-on-the-production-line (accessed September 3, 2016).

[18] Rothfeder J. At Toyota, The Automation is Human Powered. Fast Co 2017:16. https://www.fastcompany.com/40461624/how-toyota-is-putting-humans-first-in-an-era-of-increasing-automation (accessed September 5, 2017).

[19] Agrawala M, Phan D, Heiser J, Haymaker J, Klingner J, Hanrahan P, et al. Designing effective step-by-step assembly instructions. ACM Trans Graph 2003;22:828. doi:10.1145/882262.882352.

[20] Serván J, Mas F, Menéndez JL, Ríos J. Assembly Work Instruction Deployment Using Augmented Reality. Key Eng Mater 2012;502:25–30. doi:10.4028/www.scientific.net/KEM.502.25.

[21] Boothroyd G, Dewhurst P. Design for Assembly Handbook. Amherst, MA: University of Massachusetts, Dept. of Mechanical Engineering; 1983.

[22] Namouz E, Summers JD, Mocko GM. Reasoning: Source of Variability in the Boothroyd and Dewhurst Assembly Time Estimation Method. Vol. 5 6th Int. Conf. Micro- Nanosyst. 17th Des. Manuf. Life Cycle Conf., vol. 5, American Society of Mechanical Engineers; 2012, p. 611–8. doi:10.1115/DETC2012-71075.

[23] Owensby E, Shanthakumar A, Rayate V, Namouz E, Summers JD. Evaluation and Comparison of Two Design for Assembly Methods: Subjectivity of Information Inputs. Vol. 9 23rd Int. Conf. Des. Theory Methodol. 16th Des. Manuf. Life Cycle Conf., vol. 9, ASMEDC; 2011, p. 721–31. doi:10.1115/DETC2011-47530.

[24] Azmitia M. Peer Interaction and Problem Solving: When Are Two Heads Better Than One? Child Dev 1988;59:87. doi:10.2307/1130391.

[25] Müller BC, Reise C, Seliger G. Gamification in

Factory Management Education – A Case Study with Lego Mindstorms. Procedia CIRP 2015;26:121–6. doi:10.1016/j.procir.2014.07.056.

[26] Lemons G, Carberry A, Swan C, Jarvin L, Rogers C. The benefits of model building in teaching engineering design. Des Stud 2010;31:288–309. doi:10.1016/j.destud.2010.02.001.

[27] Panadero CF, Roman JV, Kloos CD. Impact of learning experiences using LEGO Mindstorms® in engineering courses. IEEE EDUCON 2010 Conf., IEEE; 2010, p. 503–12. doi:10.1109/EDUCON.2010.5492534.

[28] Verma AK. Simulation Tools and Training Programs in Lean Manufacturing – Current Status Final Report. vol. 2003. 2003.

[29] Wilcox R, Nikolaidis S, Shah J. Optimization of Temporal Dynamics for Adaptive Human-Robot Interaction in Assembly Manufacturing. Robot. Sci. Syst. VIII, Robotics: Science and Systems Foundation; 2012. doi:10.15607/RSS.2012.VIII.056.

[30] Anscombe R, Bryant A, Buckingham R, Ferguson G, Graham A, Lichon M, et al. Snake-Arm Robots: A New Approach to Aircraft Assembly. SAE Tech. Pap., 2006. doi:10.4271/2006-01-3141.

[31] Charalambous G, Fletcher S, Webb P. Human-automation collaboration in manufacturing. Contemp. Ergon. Hum. Factors 2013, vol. 1, Taylor & Francis; 2013, p. 59–66. doi:10.1201/b13826-16.

[32] Oliff H, Liu Y, Kumar M, Williams M. Integrating Intelligence and Knowledge of Human Factors to Facilitate Collaboration in Manufacturing. Vol. 1B 38th Comput. Inf. Eng. Conf., vol. 72, American Society of Mechanical Engineers; 2018, p. 135–40. doi:10.1115/DETC2018-85805.

[33] Norton MI, Mochon D, Ariely D. The IKEA effect: When labor leads to love. J Consum Psychol 2012;22:453–60. doi:10.1016/j.jcps.2011.08.002.

[34] Hong K, Nagarajah R, Iovenitti P, Dunn M. A sociotechnical approach to achieve zero defect manufacturing of complex manual assemblies. Hum Factors Ergon Manuf 2007;17:137–48. doi:10.1002/hfm.20068.

[35] Sklar AE, Sarter NB. Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains. Hum Factors J Hum Factors Ergon Soc 1999;41:543–52. doi:10.1518/001872099779656716.

[36] Lee JC, Dietz PH, Leigh D, Yerazunis WS, Hudson SE. The PHANTOM Haptic Interface: A Device for Probing Virtual Objects. Proc. 17th Annu. ACM Symp. User interface Softw. Technol. - UIST '04, New York, New York, USA: ACM Press; 2004, p. 291. doi:10.1145/1029632.1029682.

[37] Yatani K, Truong KN. SemFeel: A User Interface with Semantic Tactile Feedback for Mobile Touch-screen Devices. Proc. 22nd Annu. ACM Symp. User interface Softw. Technol. - UIST '09, New York, New York, USA: ACM Press; 2009, p. 111. doi:10.1145/1622176.1622198.