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THE DESIGN OF A DATA RECORDER TO TEST THE EFFECTS OF COLOR CONTRAST ON 'THIS SIDE UP' PICTORIAL MARKINGS ON PACKAGE ORIENTATION WITHIN UPS GROUND

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THE DESIGN OF A DATA RECORDER TO TEST THE EFFECTS OF COLOR CONTRAST ON “THIS SIDE UP” PICTORIAL MARKINGS ON PACKAGE ORIENTATION WITHIN UPS GROUND

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ABSTRACT

A data recorder was built and qualified to record package orientation over time. The device was then used to observe the effects on package orientation during UPS ground shipping of current and modified ASTM D5445-03 “This Side Up” symbols. Modified symbols on packages demonstrated the effects of contrasting color relationships on symbol noticeability and human compliance. Shipping trials were conducted through UPS distribution centers for cube-shaped packages equipped with custom designed tri-axial accelerometers. Data recorded on 112 shipments provide comparisons of four ASTM D5445-03 “This Side Up” symbols: unmodified, modified blue, modified “black and white”, and control (no symbol). Data analysis revealed package orientation changes did not differ between any of the samples for changes in orientations lasting between 1 and 3 seconds. These changes were attributed to non-human impacts, vibrations, and drops. Orientation changes lasting from 3-20, 20-3600 and greater than 3600 seconds did not differ significantly between the ASTM standard and the control. It was found that the modified blue and modified “back and white” symbols reduced the number of orientation changes from 20-3600 seconds. Statistical analysis showed that the modified “black and white symbol” significantly reduced total orientation changes when compared to the other symbols tested. Human compliance towards the modified symbols is analyzed in light of the 1924 Hawthorne experiments. The thesis describes the accelerometer construction, experimental design, and detailed results of the study.

DEDICATION

This work is dedicated to my brother Matthew W. Hurley. Without him, none of this would have been possible.

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To my advisor:

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CHAPTER ONE

I. INTRODUCTION

The most common hazards experienced during package distribution result from manhandling, warehouse handling equipment, vehicle impacts, and vehicle vibrations (Brandenburg 2001). One consequence of the dynamic environments encountered by packaging is inversion. Packages that contain liquids, loose goods, mobile components, modified atmospheres, or pressure-sensitive mechanisms have been documented to be less successful in protecting the product when inverted (Ngadi et al., 1997)

Many organizations have suggested methods to stabilize package orientation by the use of semiotics, the study of signs and symbols as communicative behavior (semiotics, n.d.). ASTM International (International Society for Testing and Materials), ISO (International Standards Organization), and ISTA (International Safe Transit Association) strongly suggest the use of pictorial markings to influence the handling of goods. These organizations recommend that the symbols be displayed in black or red. None of these symbols incorporate the theories of color and contrast on improving visual communication. Academic research, which is detailed in the review of literature, claims that currently employed pictorial markings are not effective in reducing improper handling of packages.

This study details a device build and series of tests that report the orientation of a package over time. ASTM D5445-03 “This Side Up” and modified pictorial markings were examined throughout the UPS distribution environment. A test plan and experimental design were created to determine human compliance towards a pictorial marking on a distribution package.

CHAPTER TWO

II. REVIEW OF LITERATURE

Packaging Fundamentals

"Packaging is an extraordinarily complex endeavor that must be viewed as a part of a larger system, within which every activity has some impact or demand on the package" (Soroka, 2002).

It is evident throughout any industrialized society that packaging is the means to provide product to the consumer. Properly designed packages that "[provide protection, containment, information, and utility]" (Cooksey, 2003) are less likely to be damaged and/or rejected at the retail outlet. Therefore, it is critical that individuals or corporations who produce products consider the all possible elements when specifying the attributes of a package.

For package qualification, most individuals rely heavily on published packaging standards within ASTM International, ISTA, and ISO. Designing packaging around "…proper pre-shipment testing methods, along with appropriate labels can reduce the risk of damage and injury" (Newsham 1999). After a package is prototyped, typically a series of distribution tests are preformed to qualify the package. These tests require expensive simulation equipment that imposes a variety of vibrations and impacts on packaged products. The results yield critical information that allows the packaging scientist to further optimize the package with regard to expected distribution hazards.

There are no standards regarding the testing and qualification of package communication. After days of research, development, package design, package qualification, distribution analysis, and detailed specifications, if it is determined that a package should not be inverted, a simple black or red "This Side Up" label is applied to a panel. If shock and impacts are found to be a direct cause of product damage, then a "do not drop" label may be applied to a panel. If rough handling is found to be a direct cause of product damage, then a "Fragile – Handle with Care" label is applied to a panel. These symbols are assumed to be effective irrespective of the culture or language of the interpreter, as the publishers are international organizations. Further, no specifications are provided regarding the size of the symbols relative to the size and shape of the packaging.

These simple precautions are insufficient for proper packaging design.. If the structure of the package requires cross-functional communication and engineering testing, the information displayed should also be qualified. If after expensive equipment is utilized to determine that specific drop heights or improper package orientations are found to be problematic, a simple untested symbol does not suffice.

Packaging Design Methods

Only design methods and theories relevant to this specific research will be discussed. Improper packaging "has the potential to result in excess damage and waste, diminish shelf life, and loss of flavor or efficacy." (Bix et al., 2004) Bix defines packaging design as a "socio-scientific endeavor" where "packaging is not just a means to protect or contain the product, but has the potential to impact the decisions of consumers, and the lives of those interfacing with it" Therefore, packaging plays a critical role in protection, containment, information and utility.

Designing for product protection is one of the many responsibilities of a packaging scientist. After generating ideas through creative brainstorming, an ideal material is chosen for the primary package (for example, glass, paper product, metal, or plastic). Typically, CAD (Computer Aided Design) software is used to design the structural and geometric properties of the package. Once completed, specifications are created, materials are sourced, the primary packaged is prototyped (virtual and/or physical), and the secondary, tertiary, and quaternary systems are designed. Depending on the customer, an indirect seller or direct user, the secondary packaging is designed. A secondary package surrounds the primary package, but is not used as a distribution package. A common secondary package is a cereal box, where the paperboard carton contains the primary plastic bag. Some customers prefer multiple packaged products in one container, commonly referred to as a tertiary package. Typically, tertiary packages are RSCs (regular slotted containers) from corrugated fiberboard, HSCs (Half Slotted Containers) from corrugated fiberboard, or plastic totes. Depending on the design and material choice, a tertiary and/or quaternary package system may be designed. If the customer desires multiple cases of packaged products, then a quaternary pallet is utilized. Quaternary packaging software exists (CapePack and TOPPS) that allows an engineer to input the package or case dimensions, pallet size and material, gross weights and dimensions, and which outputs the most efficient nesting of packages on a pallet.

Secondary and tertiary packages must be able to contain the primary packages throughout the rigors of the distribution environment. If the package is altered in any way to allow the end customer, wholesaler, or retailer to dispense or remove the product, then the remaining products must be held in their proper orientations during use or removal.

The design of information is equally important to the design for protection and containment of a packaged product. Many products have intended uses or consumption limits that could result in injury. "Functional communication provides consumers with information that is needed to use, store and handle products safely and effective" (Bix et al., 2004). Depending on the product, distribution method, distributor, seller, and legal requirements, specific information may be required to be printed on a package.

Not only is the printed information important, but also how the information is designed. "The choice of color and typography in labeling often plays an important role in the acceptance, use, and customer response, as well as the cooperation of the dealer. It can even be said that the success or failure of a packaged product can be attributed to the manner and style in which it is identified" (Hanlon et al, 1998). Information also plays a key role in the handling of a package within the distribution environment. ASTM D5445 symbols and ISO Standard 780, *Packaging Pictorial Markings for Handling of Goods*, each provide a list of suggested symbols that pertain to controlling package handling.

Information design encompasses a variety of perceptual theories that can influence the noticeability of a pictorial marking. When information is designed with two parts, a figure and a ground, information can be easily recognized and removed from environmental interferences (Vecera, et al, 2002). For instance, if the "This Side Up" (Figure 1) pictorial marking were to be designed with a white "ground" and contrasting black arrows, the "figures," the marking would exemplify a figure-ground relationship that "receives more attention and is better remembered" (Lidwell et al, 2003).

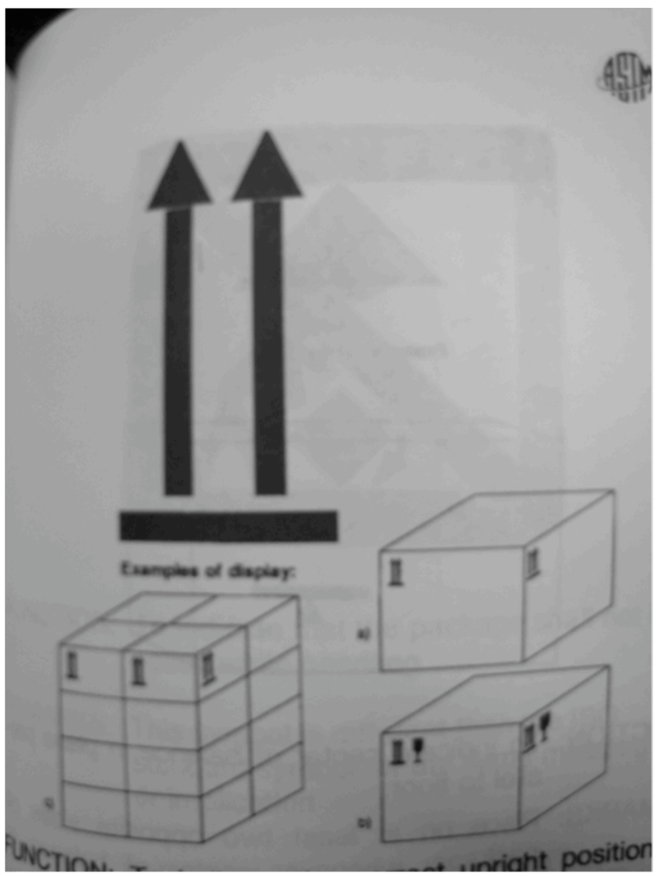

Figure 1. ASTM D5445-03 "This Side Up" Pictorial Marking

Another information design theory is the golden ratio. This "divine proportion" has existed throughout all artistic styles and is a commonly applied ratio in architecture. The golden ratio is "a ratio within the elements of a form, such as height to width, approximating 0.618" (Lidwell et al, 2003). Leonardo da Vinci incorporated this ratio into his paintings. The Parthenon, the Great Pyramid of Giza, Chartres Cathedral, and Stonehenge all illustrate aspects of the golden ratio (Lidwell et al, 2003). Even if this mathematical proportion has no cognitive effect on an individual, it is still grounded in the human perceived notion of beauty and harmony. The greatest monuments, works of art, and exquisiteness in the world commonly exhibit the golden ratio.

In a similar way to the golden ratio, the Gutenberg diagram provides a systematic process to improve visual communication. The method of reading information in western cultures is outlined in the Gutenberg diagram. This diagram "describes the general pattern followed by the eyes when looking at evenly distributed, homogeneous information" (Lidwell et al, 2003). The Gutenberg diagram illustrates that people initially observe an object in the upper left corner and swoop diagonally towards the bottom right corner. The eye slightly touches the upper right corner, yet pays the least attention to the lower left corner. This mapping of the eye is only found in western cultures where people read left to right and downward. This would not be the most effective way to communicate to many Asian audiences. Retail packaging design typically takes advantage of this concept by placing brand logos in the upper left corners and less important information in the lower left corners. Promotions and give-a-ways are commonly located in the bottom right corners where perceptual observation terminates.

Many utility features on a packaging system are advertised using the concepts of the Gutenberg diagram (Figure 2).

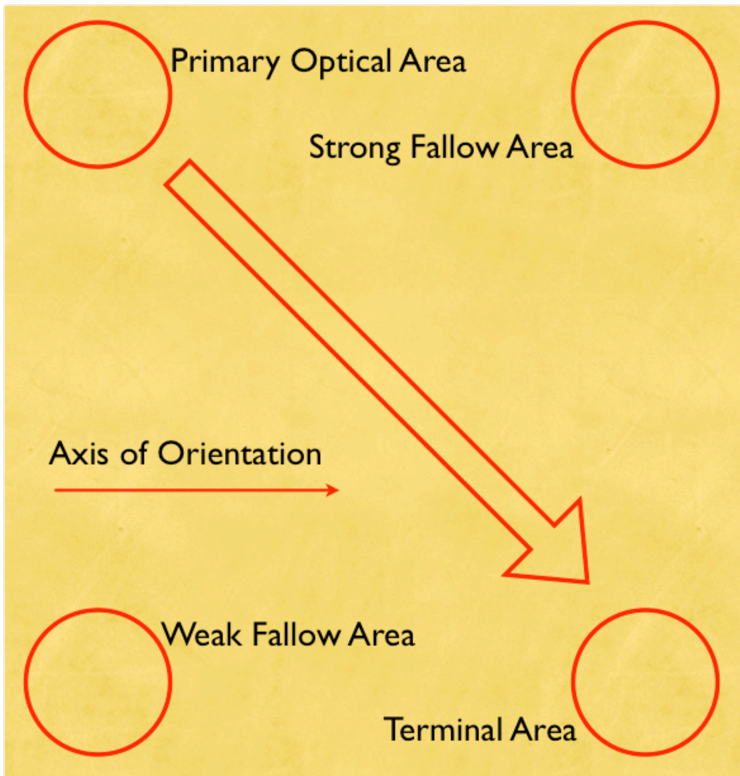

Figure 2: Gutenberg diagram.

Utility is related to the ease of use of a package system. This encompasses the opening, closing, dispensing, legibility, storage, and disposal of a package. Many times unique utilities are displayed boldly on the package, which "are often the driving force for the sales of the product" (Singh 2005). Utility is increasingly becoming an importantly attribute of packaging as society ages (Bix et al., 2004).

Each aspect of the packaging design process must be carefully considered. Every attribute of the package should have a tried and tested purpose. This should be consistent for information directed towards indirect and direct users. One very important user of packaging is the distribution environment. Much of the information designed on distribution packaging is targeted towards these individuals.

The Single Parcel Environment

This nature of this research does not require a holistic understanding of the distribution environment, but only of the single parcel environment. Typical distribution environments make use of container truckloads that are predesigned for maximum efficiency of packages per truck. In contrast, individuals shipping through the single parcel environment typically do not produce enough packages to take advantage of full truckloads. Companies and individuals who ship single parcels have little impact on the organization of the transport system as they have no control over what items are placed in the cargo area with their package. The most commonly used single parcel networks are UPS, FedEx, and DHL (Singh 2004).

The primary contentions of this study are that package orientation is an essential aspect of distribution, and that printed information on the package should be tested for handler compliance. The handler is the individual employed by the parcel environment to assist in the proper delivery of the package. Compliance is defined as the proper behavioral performance of the handler. One method to determine handler compliance is to place pictorial markings on a package, mail it, and record the orientation over time. The orientation of a package is defined by the position of a package relative to the panel facing upwards. Each panel on a package receives a numerical value similar to game dice. Using the numbered panels, an accelerometer could record the specific orientations of the package during the shipment.

An accelerometer is a device that measures how quickly speed changes. Change in speed is also known as acceleration. Accelerometers are found throughout various electronic equipment; video-game controllers use accelerometers to detect tilt and rotation, while sensors that notice movement use accelerometers to detect collisions. The core mechanism of a car alarm is an accelerometer that detects vibration. With the advent of MEMS technology (micro-electro-mechanical-systems), modern accelerometer cores are enclosed domes with a small heater and thermocouple. The air that is heated rises and the thermocouple detects the deflection of the heated air off the center. This is a measure of acceleration applied to the sensor. Because the device is recording information from within a three-dimensional object, data are recorded for three planes. The letters X, Y, and Z identify each plane. X is the horizontal plane, Y is the vertical plane, and Z is the dimensional plane (Parallax, 2008).

A review of academic journals provides a handful of studies on package handling throughout the single parcel environment. Unfortunately, packaging orientation, shock, drop, and impact analysis of the distribution environment conflict with each other. Newsham reports three major findings in his distribution analysis throughout UPS: "generally RSC shippers are positioned in their expected top orientation by loading and sortation employees, …in most cases the package is positioned with the shipping label in the top orientation during loading or sortation, …[and] pictorial marking will help if the package shape and shipping label positioning is in a non-conventional mode" (Newsham, 1999). Another author reports that, "warning labels reading 'Fragile-Handle with Care' had no significant effect on the handling of packages in the FedEx system" and "labels had [no] significant effect on the severity of drop heights" (Singh 2004). Though these studies utilized different distribution companies, further investigation into similar publications from the same authors reveals that "handling environments within FedEx and UPS are not significantly different between ground shipping, second-day and next-day, regardless of package size and weight of packages" (Singh 2004). Many distribution tests that study the effects of pictorial markings, warning labels, and handling of packages throughout single parcel environments use less than fifty test samples to make observations on the system. Paul Singh reports that he utilized "a total of 48 trips…to collect the data for [a] study" throughout the DHL small parcel environment (Singh 2004).

Distribution studies that analyze various parcel environments report, "the data [second-day air Federal Express small and light-weight packages] showed that neither the package size/weight nor the labels had any significant effect on the severity of drop heights"(Singh et al, 2004) Further, "the high incidence [60%] of face drops found…that these impacts are the result of automated handling operations, not drops." Singh further reports that, "the distribution of impact orientations and the lack of correlation between package size and weight and drop height suggests that impact severity and location are mainly the result of automated handling operations rather than actual drops" (Singh 2007).

UPS was chosen for this study as literature indicates that it is the most widely used package shipping system. Singh reports "UPS is the largest US parcel carrier, and the vast majority of its shipments are ground (Singh 2004)." UPS is also considered "the world's largest package delivery company" (Parcel Service, 2008). Within the UPS system, Louisville International Airport contains UPS's prized 1-billion dollar package hub. It is described as the company's "crown jewel" and "world class" (Lovel, 2002).

In summary, the small parcel environment has a large set of dynamic forces that affect packaging. In spite of the ubiquitous use of pictorial markings and their specification by all of the standards organizations, the existing literature claims the effectiveness of pictorial markings is limited. Thus, in order to utilize package communication in an attempt to have more control on the small parcel environment, the study of symbols must be considered.

Semiotics

Semiotics is the study of signs, symbols, warnings, and graphic images that communicate a behavioral action. Behaviors that are translated into signs, symbols, warnings, and graphic images are considered iconic representations. There exist four categories of iconic representations: *similar*, *example*, *symbolic*, and *arbitrary* icons. *Similar* icons depict images that are "visually analogous to an action, object, or concept" (Lidwell, 2003). These symbols represent simple and uncomplicated actions. The ASTM D5445-03 "This Side Up" symbol, which is the particular interest of this study, is a *similar* icon. Figure 3 shows a right turn symbol, which is also an example of a *similar* icon. *Example* icons "use images of things that exemplify or are commonly associated with an action, object, or concept" (Lidwell, 2003). These icons are useful when illustrating a complex activity. Figure 4 depicts a fragile symbol, which is illustrative of an *example* icon. Symbolic icons use images of established entities. These actions are easy to recognize. Figure 5 shows an airport symbol, which is an example of a *symbolic* icon. *Arbitrary* icons require prior knowledge about the symbol. *Arbitrary* icons do not resemble the behavior they are representing and must be learned for compliance to occur. Figure 6 shows a radioactive symbol, which is an example of an *arbitrary* icon.

Figure 3. Similar Icon: Right Turn Symbol (Lidwell, 2003)

Figure 4. Example Icon: Fragile Symbol (Lidwell, 2003)

Figure 5. Symbolic Icon: Airport Symbol (Lidwell, 2003)

Figure 6. Arbitrary Icon: Radioactive Symbol (Lidwell, 2003)

Semiotics also encompasses the discourse between the symbol and the interpreter. There is a well-documented model for effective information processing that outlines four steps of interaction (Rousseau 1998). First, information must be noticed. A recent study of warning icons noted, “warning design factors on currently available containers are not very noticeable” (Laughery et al, 2003). Specific research towards distribution symbols noted that the ASTM D5445-03 “Do Not Drop” pictorial marking was not effective in reducing the number of drops throughout the FedEx single parcel system (Singh, 2004).

Second, the noticed information must be encoded into memory. Encoding information into memory involves decoding the message through the perceptual system. Lastly, the message must be comprehended and then complied with by the viewer. Successful navigation through these steps depends on the environment of interaction, the design of the information, and the interpreter within the system; see Figure 7 (Bix, 2008). Similarly, Mary Huer's studies of perceptual grounding show that cultures do not interpret symbols consistently. Huer's research analyzes information translucency between different cultures and notes that African-Americans and Mexican-Americans interpret graphic symbols significantly differently from European-Americans (Huer, 2000).

It is highly debated that many signs and symbols are grounded into human visual perception. A grounded symbol is a pictorial marking that is understood without thought processing, similar to green and red traffic lights. Within western cultures, "spatial words such as above, below, left, right, around, and in are grounded in visual perception" (Anonymous, 2007). If some symbols are grounded in perception, then the understanding must have originated in the unconscious. Lawrence Barsalou reports that "perceptual symbols function unconsciously, as during preconscious processing and automatized skills. Most importantly, the basic definition of perceptual symbols resides at the neural level: unconscious neural representations" (Barsalou 1999).

Another significant aspect of symbols is color. Researchers agree that varying the color of background and type in printed matter affects legibility" (Bix, 2003). Because color contrast between the background and foreground affects noticeability, it is reasonable to measure the difference to maximize potential behavioral compliance. The School of Packaging at Michigan State University completed a series of experiments with color that revealed black on white contrast on printed matter is the "easiest to read" (Bix, 2003). Further, Dr. Bix noted in her "Six Guidelines for Designers [that] dark text on a light background is desirable" (Bix, 2002).

Figure 7. Factors Affecting the Success or Failure of Information (Bix, 2008)

Color Theory

Color theory is a process of using color in an organized fashion to create harmonious and pleasing thoughts for the viewer (Morioka, 2006). Color is traditionally grouped into workable combinations on the color wheel. For the research, it is important to note that complementary color groupings "represent the most contrasting relationships" (Morioka, 2006). Complementary colors are pairs of colors that exist opposite of each other on the color wheel (Figure 8). As previously noted, contrasting colors within symbols tend to have the greatest noticeability – which is a step in influencing human information processing.

Figure 8. A Color Wheel Illustrating Complementary Colors (Morioka, 2006)

The most widely published study on the psychophysical attributes of color is the Stroop Effect (Stroop, 1935). JR Stroop created a test of conflicting colors and words, and analyzed the occurrences of wrong observations. For example, a human subject was presented a sheet of paper with the words red, green and blue repeated. A select number of the words would be colored incorrectly; for instance, the word “red” may have been colored green. The test subject was given a short time frame to verbally read the paper, and the number of wrong correlations was recorded. It was commonly found that the incongruence between color and word result in a mental interference (Stroop, 1935).

The Swedish Defense Research Agency reports that color includes definite cognitive aspects, “in terms of behavioral, neuropsychological, and neurophysiological data” (Derefeldt et al, 2004). In effect, socially conditioned colors have a mental and behavioral effect on humans. In support of this theory are color studies completed with PET (positron emission tomography) measurements. It has been documented that attention to normal and abnormally colored objected triggered different parts of the brain during PET scans (Corbetta 2003). This research proves that color has an impact on cognitive processing beyond simple perception. Normal and abnormal color combinations activate different parts of the brain.

It is clear that color has an effect on human behavior. Color combinations trigger different parts of the brain, reactions to specific colors are ingrained into human memory, and colors that conflict with expectations create mental interferences. In a sense, color has an environmental effect on the viewer. One of the most insightful studies on environmental perception and behavior is the Hawthorne Studies.

The Hawthorne Effect

In a study involving introducing changes to an environment, it is necessary to consider the possible human reactions towards the changes. Many studies have been conducted to monitor the effectiveness of environmental factors on human productivity. The most renowned studies concerning human reactions to environmental changes are the Hawthorne experiments.

"The Hawthorne Studies were the single most important investigation of the human dimensions of industrial relations in the early 20th century" (Brannigan, 2001). They were performed at the Bell Telephone Western Electric manufacturing plant in Chicago in 1924. Bell employed over 24,000 people who made telephone equipment. During the time of the great depression, the demands for parts were so low that research was the only sustainable alternative. The Hawthorne plant became a center of research and development for the company. The Hawthorne experiments studied a variety of environmental changes on employees. Lunch breaks were periodically and randomly increased, shortened, and also removed. Light intensity was increased and decreased. The workweek was also periodically extended, shortened, and at one point workers were allowed a week of free vacation. It took over 15 years to release the data as it clearly illustrated that plant management "was virtually incapable of controlling worker output let alone assessing appropriate levels of productivity" (Brannigan, 2001). It was found that regardless of what was changed, "the average hourly output per week during the study appears to drift upwards, period after period, even during the phase in which the pauses were cancelled and the longer workweek restored" (Brannigan, 2001). After studies of removing the lunch break and providing a company sponsored lunch break, increasing and reducing light intensity, and reducing and extending the workweek, productivity increased during each trial by 30 to 60 percent. There was, of course, a shelf life to the productivity; yet no specific conclusions were drawn about the shelf life.

The overall learning from the Hawthorne studies is that "employees are more productive based on their belief that changes made to the environment will increase productivity" (Lidwell, et al 2003). This theory can be applied to semiotics. If a pictorial marking were to be constructed that was different and easier to notice, then compliance towards the symbol should increase. The length of time of increased effectiveness is unknown, but as long as change is introduced into the environment, a steady state of increased compliance towards the symbol should be observed.

CHAPTER 3

III. MATERIALS AND METHODS

Hypothesis – Data Recorder

Based on the review of literature and prior research conducted in package distribution analysis, a hypothesis was formulated that a data recorder could be designed and produced which recorded package orientation over time. The goals of the build were: (1) to design an easy-to-use unit; (2), to program the device so data could be immediately read and analyzed in Microsoft Excel; (3) to minimize cost; and (4) to qualify the unit on an ISTA 1G test against an IST EDR-3 commercial accelerometer.

Hypothesis – Effectiveness of Package Markings

The qualified data recording device would be used in a designed experiment to test the effectiveness of pictorial markings during shipment and handling through a single parcel distribution environment. It was hypothesized that ASTM D5445-03 pictorial markings were not effective in communicating to package handlers throughout the single parcel environment. Because prior research concluded that the ASTM D5445-03 "Do not Drop" symbol had already been analyzed, the "This Side Up" symbol was selected for study. A second hypothesis was conceived that if color and contrast were incorporated into modified ASTM D5445-03 "This Side Up" symbols, then less package inversions would occur because the symbol noticeability would increase.

Test methodology

To test the hypotheses, qualified data recorders were placed into box samples displaying symbols. Box samples were designed with four test symbols: a control (no symbol), an unmodified ASTM D5445-03 “This Side Up” symbol, a modified blue ASTM symbol, and a modified “black and white” ASTM symbol.

Data recorder design and construction

A two-step approach was required to develop a data recorder meeting the test requirements. First, a mechanical data recorder was built, but failed during qualification. In response, a second data recorder was built using advanced accelerometers. This device performed satisfactorily and eight identical devices were built to conduct the study.

Minimum success requirements for the data recorder

Due to the timeframe of the project, eight devices capable of recording package orientation were required to complete the research on time. These devices needed to fit securely into a 12 in. x 12 in. x 12 in. box. A one cubic-foot box was used to prevent preference towards a particular box panel due to the box shape. The device needed to be able to constantly record orientation (every second) for at least 16 days. The device needed to be able to output data without modification to the unit, such that recipients could be instructed to download and email data from the unit. The device required encoded data in Excel-format to allow users of various operating systems and software to view data.

After the physical construction of the device, it needed to be able to withstand and record correct data during an ISTA 1G qualification. ISTA 1G is commonly referred to as an “intense and rigorous test” (Dunno, 2008). During an ISTA 1G test, packages undergo a series of extreme vibration profiles and drops on different panels. The device must also provide visually equivalent data when compared to a commercial accelerometer.

The Initial Data Recorder Build

The initial data recorder build was an electro-mechanical device that relied upon gravity to detect orientation. First, a two-part structure with six cavities was designed in Solidworks. The cavities were linked by channels, which were large enough for a silver ball to pass through. The cavities were cored equidistant around a center, which simulated the relative faces of the primary package (Figure 9). Placed inside the channel in advance of the cavity were the end-points to a tally counter circuit loop. Six small tally counters were rewired so the counter increased when the circuit was completed (Figure 10). Small silver balls were hand fabricated by a sponsoring jewelry store to fit the application (Figure 11). When the device was rotated, the silver ball would roll from one cavity to another, triggering the tally counter and providing a digital read on the number of completed circuits. The recorded value was divided in half to calculate an actual count (the silver ball triggers the tally counter twice for the entrance and exit).

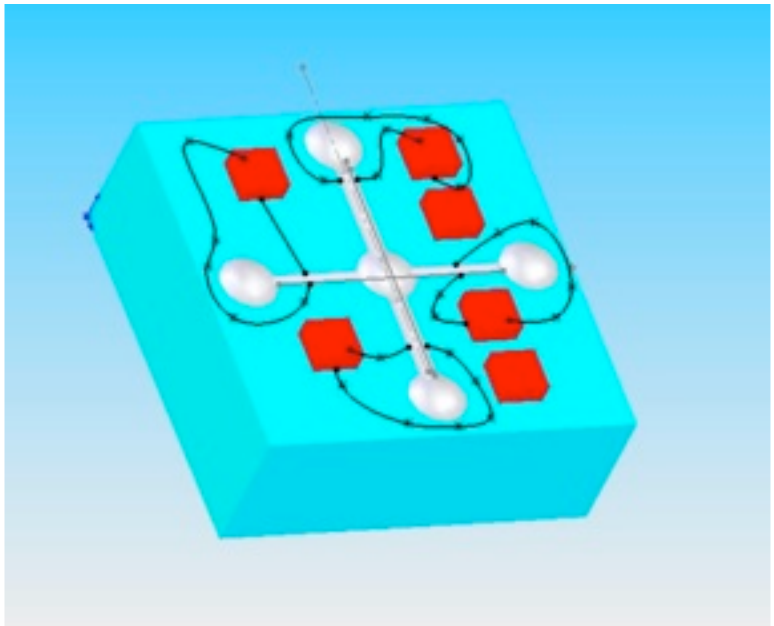

Figure 9. Initial Data Recorder Concept

Figure 10. Talley Counter

Figure 11. Silver Spheres

The device was prototyped on a Dimension BST 768 (Figure 12) machine and set into a package for testing. When an ISTA 1G test was preformed using a Lansmont Vibration Machine (Figure 13), the device was unable to record proper orientation. Resonant frequencies caused the silver spheres to bounce vertically and trigger other tally counters. The device was redesigned with curved channels to prevent improper counter triggering, yet the device was unable to record package tumbling, changes in orientation within 1 to 3 seconds, or rolling drops which hit multiple faces of the package. As a result of these issues, it was decided to design a device that utilized a modern tri-axis accelerometer.

Figure 12. Dimension BST 768 Rapid Prototyper

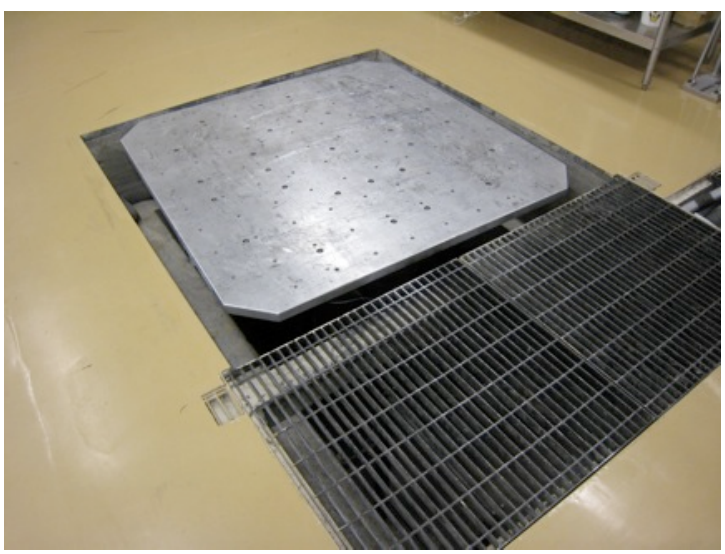

Figure 13. Lansmont Vibration Table

Second and Final Data Recorder Build

A new device was devised using an accelerometer to eliminate reliance on gravity and mechanical structures. During preliminary testing, it was found that the accelerometer's sensitivity led to the recording of hundreds of thousands of data points. Therefore, in order to remove unnecessary data, a software program was designed capable of processing informative groups of data.

A Parallax Basic Stamp Super Carrier board was used to mount the data collecting devices. The carrier board featured a 3"x 4" double-sided platform, BS1 and BS2 modules (Basic Stamp), an on-board voltage regulator (6-30 VDC) from a wall-pack or battery, a serial programming port (DB9) for run-time communication with BS2 (Basic Stamp 2) code, and accepted standard computer interfaces (Figure 14).

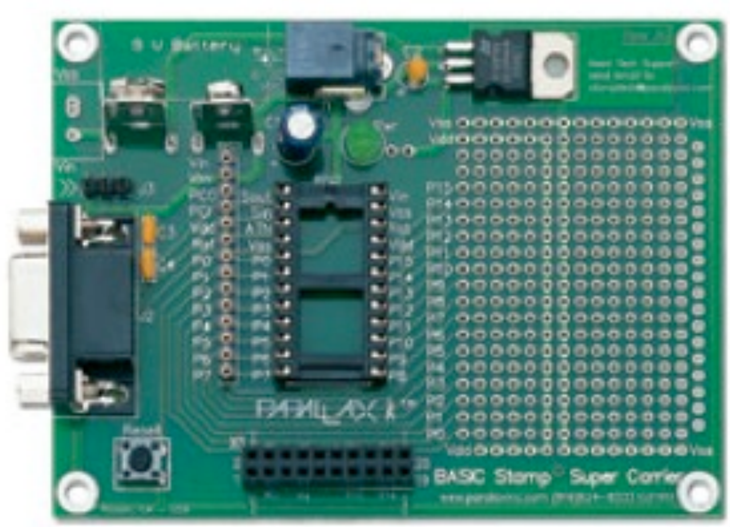

Figure 14. Parallax Basic Stamp Super Carrier Board (Parallax, 2008)

Attached to the Parallax Basic Stamp Super Carrier Board was a Hitachi H48C Tri-Axis Accelerometer Module. The accelerometer detects a gravitational force of +/-3g on three axes. The device contained an onboard regulator at 3.3 volts with analog signal conditioning. Also, a MCP3204 (four channel, 12-bit) analog-to-digital converter interpreted the device's voltage output. The module required a 0.7" by 0.8" board size. Basic Stamp® serial commands linked the interface in real time. The device utilized calibration-free MEMS technology to detect orientation (Figure 15).

Figure 15. Hitachi H48C Tri-Axis Accelerometer Module (Parallax, 2008)

To process the components on the Super Carrier Board, a Basic Stamp2® microcontroller was installed. With a processing speed of 20 MHz, the device could execute over 4,000 instructions per second. The microcontroller included 32 bytes of onboard RAM and had dimensions of 1.2"x 0.6"x 0.4" (Figure 16).

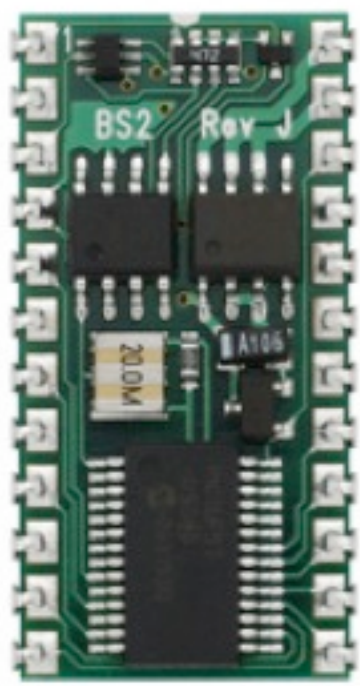

Figure 16. Basic Stamp2® microcontroller (Parallax, 2008)

To store data on the device, a SD data logger was soldered onto the Super Controler Board. This custom built device was provided by Hitt Consulting, LLC. Each module could accept an SD card and record up to 32 megabytes of data. Raw data from the SD card could be imported directly into Microsoft Excel. The data logger had a footprint of 1.5"x 2.0" and accepted the Super Carrier Board onboard power unit. The unit was also equipped with an LED indicator light which was helpful in device testing (Figure 17).

Figure 17. Hitt Consulting, LLC SD Data Logger (Hitt Consulting, 2008)

The completed and soldered control board measured 4"x 3"x 0.75" (Figure 18). A custom ABS (Acrylonitrile Butadiene Styrene) device case was designed in Solidworks and built on a Dimension BST 768 (Figure 19). The case held the controller board and accessories on the bottom half of the two piece build (Figure 20). The battery pack was secured in a separate location to remove internal resonance vibrations caused by unsecured parts. The case was designed to allow test recipients easy access to the memory card. The memory card was installed on the top panel of the case, protected by a sliding mechanism which opened for maintenance (Figure 21). The two-piece construction of the ABS case prevented unintentional tampering with the circuitry of the device. All sliding and opening mechanisms were designed with a 0.01” difference as this was the building limitation of the Dimension BST 768 rapid prototyper.

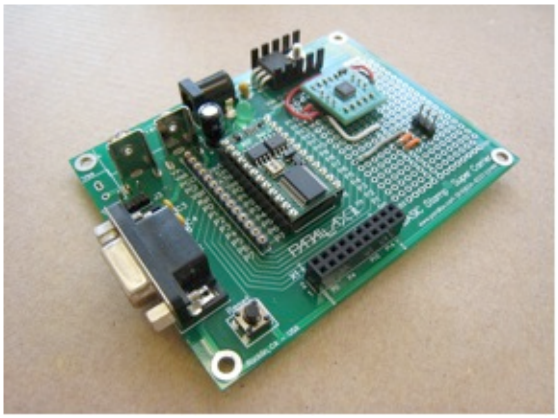

Figure 18. Completed and Soldered Control Board

Figure 20. Two-Piece Build View

Figure 19. Completed ABS Case

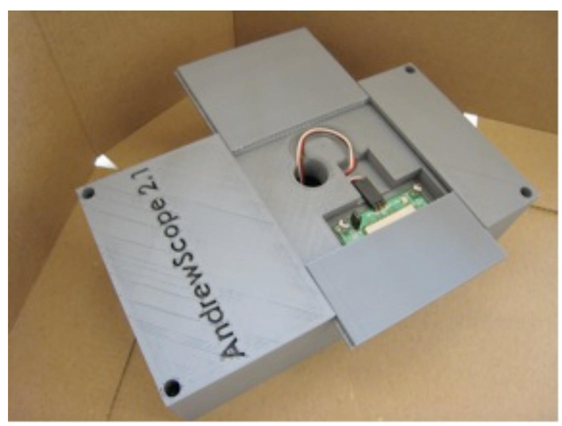

Figure 21. Sliding Mechanism Access

After the controller board was soldered with all accessories and installed into the ABS case, a Visual Basic 2 program was designed to allow all of the components to communicate with each other. Appendix B details the program code, which was designed by my brother Matthew Hurley. The major variable in constructing the program code was setting the orientation limits of the accelerometer. The accelerometer does not require calibration and outputs an arbitrary, numeric value for the direction of gravity (the orientation). The device was programmed to trigger a count in orientation change when the device was oriented 10% towards the next panel. For example, if the package were to roll over on another panel, the accelerometer was programmed to record a change when the unit reached 90% of the roll to the next panel. This was programmed to record tumbles and rolls, as these are instances of incorrect orientations. The device qualification is detailed in the results section.

Shipping Package Design

A shipping package was designed around the data recorder to protect and facilitate the planned experiment. I-125 caliper C-flute corrugated unbleached Kraft fiberboard was donated by Pratt Industries in bulk to maintain consistency in the testing. A FEFCO (European Federation of Corrugated Board Manufacturers) F0204 RSC measuring 12”x12”x12” was designed to hold the accelerometer along with ample cushioning material to prevent the device from moving in the container (Figure 22). The dieline was prototyped on a DataTech 9600 (Figure 23). EPS (expanded polystyrene) foam, approximately four inches thick, was used as the cushioning material around the device. Note that the use of cushioning in package systems is a study of its own. Damage boundary curves and specific cushion design was not carried out as the objectives were to determine package orientation, not to reduce shock.

When designing a RSC, it is important to consider and properly design headspace. Headspace is the “clearance between the top of the contents inside the box and the interior face of the top of the box” (Marcondes, 1994). Because the accelerometer and cushioning are designed to take the expected loads of UPS shipments, no headspace was included into the design. Figure 24 illustrates how the accelerometer was packed into the RSC with the surrounding blocks of foam cushioning.

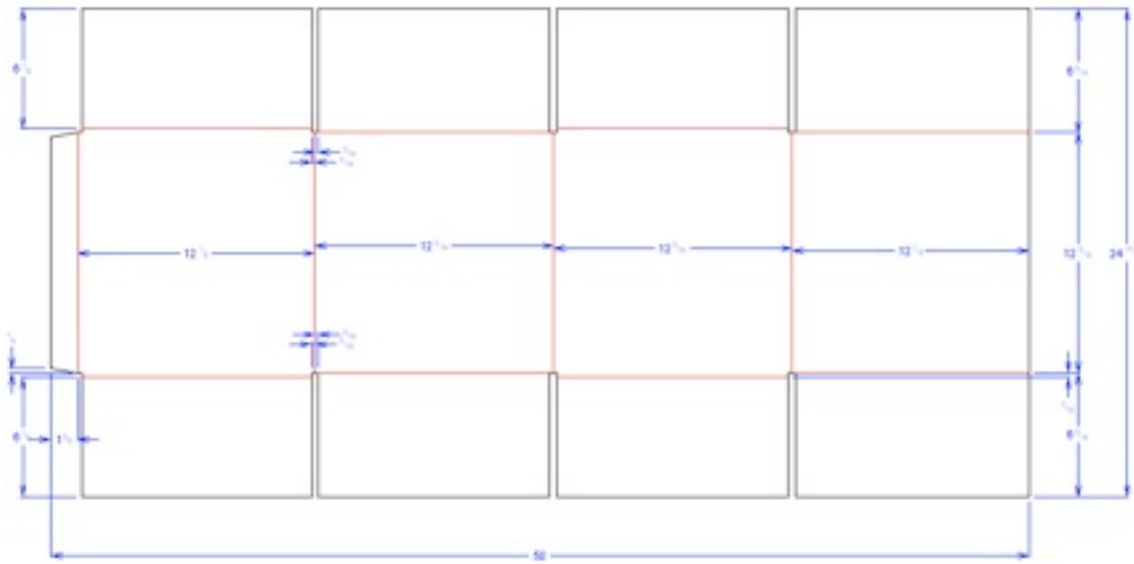

Figure 22. RSC Dieline

Figure 23. DataTech 9600 Sample Table

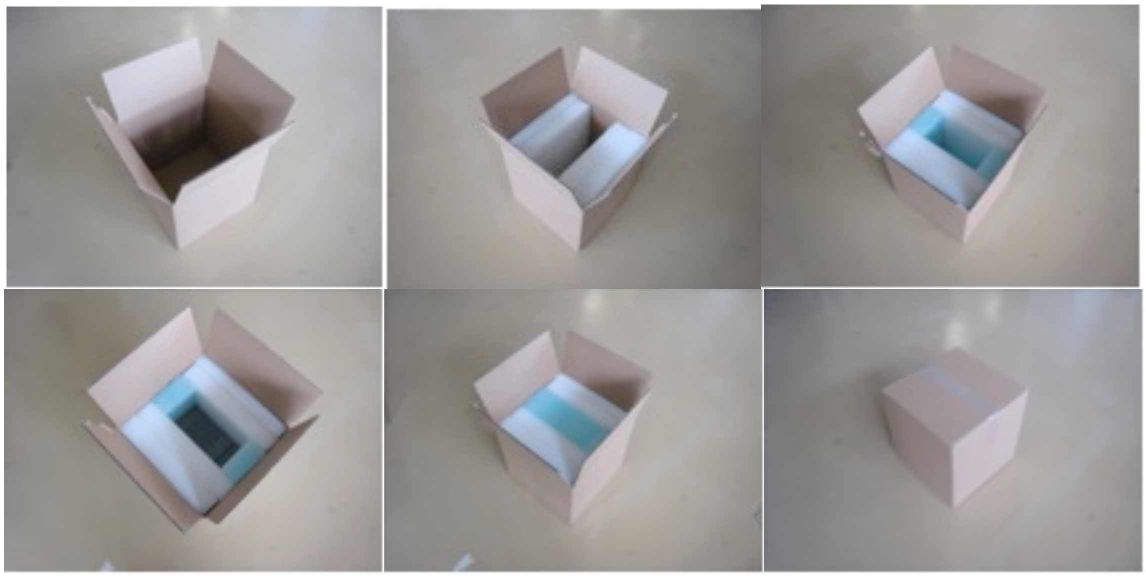

Figure 24. Accelerometer Packaging into RSC

The average weights of the box samples were 3.5 pounds. Similar distribution research used RSCs weighing 6.5 pounds (Singh 2007). This difference in weight is directly due to the data recorder used. Eight box samples were initially constructed for the study. Two received no symbol, two received ASTM D5445-03 “This Side Up” symbols using Krylon 51602 “Flat Black” spray paint, two received modified ASTM symbols using Krylon 53546 “Global Blue” spray paint, and two received modified ASTM symbols using Krylon 51602 “Flat Black” and 51502 “Flat White” Spray paint. The “Global Blue” color was chosen because the color closely resembled the ideal maximum color contrast to unbleached kraft fiberboard. The “Black and White” symbol was chosen because it represents the greatest contrast of light. Black and white also presents a clearly defined figure (the black arrows) and ground (the white background).

A stencil was designed on Adobe Illustrator and cut on the DataTech table. The stencil symbol measured 4.5”x2.0” and the background for the contrast symbol measured 5.0” x 3.5” (Figure 25). The individual arrows were designed so that the ratio of the width to length equaled the golden ratio of 0.618. All symbols were masked to the board in the upper left corner and colored. The upper left corner was chosen because it is the primary optical focus area described in the Gutenberg diagram. Also, the ASTM D5445-03 procedure states that the symbols must be displayed in the upper left corners. The pictorial markings on each box are displayed in Figure 26.

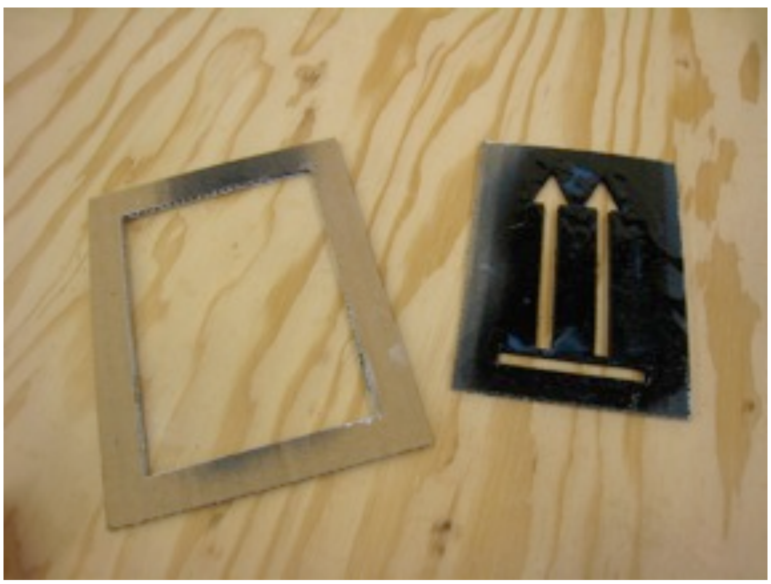

Figure 25. Symbol and Background Stencils

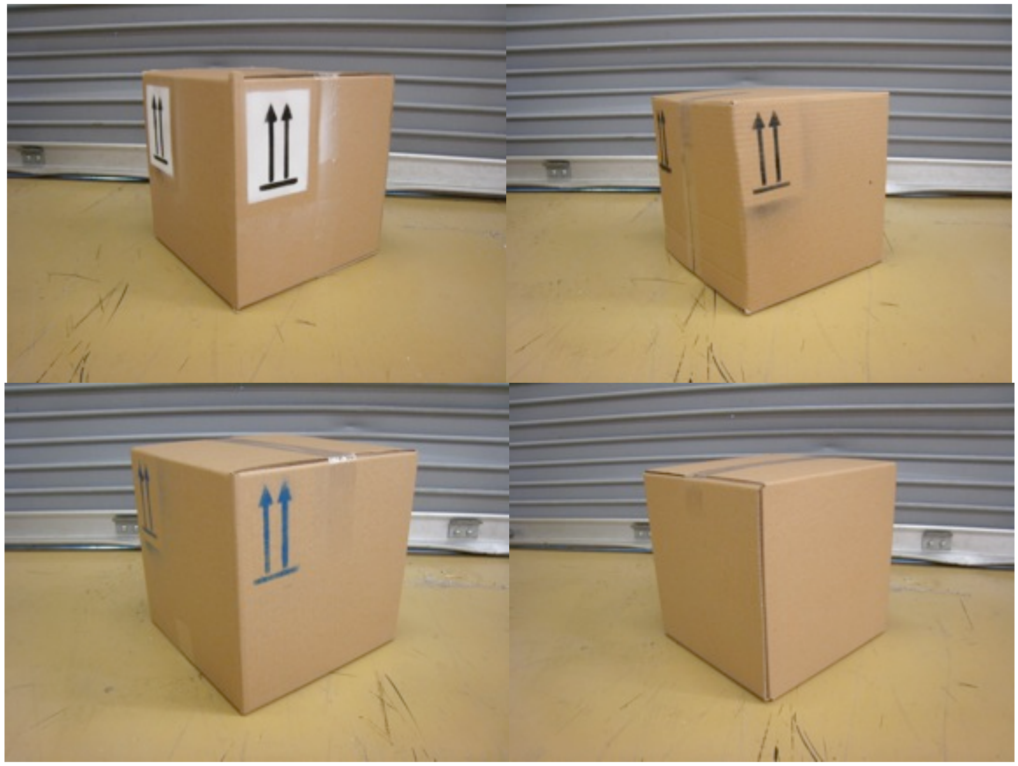

Figure 26. Pictorial Markings on Box Samples

CHAPTER 4

IV. EXPERIMENTAL DESIGN

Device Qualification

Eight test samples were constructed, fitted with accelerometers and marked with the desired symbol to be tested. An ISTA 1G test was performed to determine if the data recording devices could correctly record orientation changes. ISTA 1G is a random vibration and drop series for packaged products weighing 150 lbs or less. Samples were tested at ambient temperature and humidity. Each panel on each test sample was labeled 1 through 6 to reference back to the orientation recorded. The sample to be tested was placed on the Lansmont Vibration Table and secured with steel jigs that prevented the package from falling off the table (Figure 27). A random vibration sequence was first completed with an overall G_{rms}(route-mean-square acceleration) level of 1.15. Table 1 shows the accelerations emitted by the vibration table. After the vibration profile, the packages were dropped on each face, corner, and edge using a Lansmont Free Fall Drop Tester (Figure 28). Though ISTA 1G does not require each face, corner, and edge to be tested, this was completed to determine that each face of the box could be properly recorded.

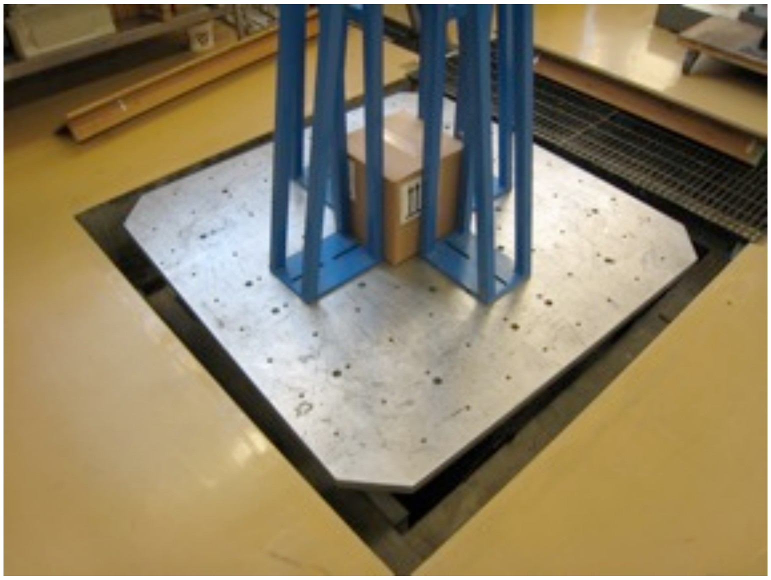

Figure 27. Box on Lansmont Vibration Machine

Figure 28. Lansmont Free Fall Drop Tester

Table 1. Acceleration vs. Frequency Profile Breakpoints

Face and Time	Frequency (Hz)	PSD Level (g2/Hz)
Face 3, 30 minutes	1.0	0.0001
Face 1, 10 minutes	4.0	0.01
Face 2, 10 minutes	100.0	0.01
Face 6, 10 minutes	200.0	0.001

Because the accelerometer used in the study was used to analyze orientation data only, acceleration data were not recorded. These accelerometers were equipped with MEMS technology, so they did not require calibration. This type of accelerometer will log an error statement if internal checks fail. The method used to qualify each individual data recorder was to complete an ISTA 1G for each data recorder and compare the scatter plots for consistency.

The data recorder built for this study was also compared to an IST model EDR-3 tri-axis accelerometer (Figure 29). The EDR-3 unit is programmed to display peak loads on each axis as well as maximum drop heights. These data could not be compared to the data recorder in this study, but the direction of gravity recorded by the EDR-3 also depicts the unit record of orientation. The value (positive, negative, or approaching zero) for each peak load recorded by the EDR-3 was compared to the raw data output of the data recorder built for this study. If the EDR-3 recorded similar values, it was concluded that both record orientation equivalently.

To compare the EDR-3 to the data recorder designed for this study, the EDR-3 was placed on top of the data recorder (Figure 30), placed in the same shipping container used for the study (Figure 31) and dropped at a height of 10” on each panel. The raw data from each unit were analyzed for consistency.

Figure 29. IST EDR-3 Tri-Axis Accelerometer

Figure 30. EDR-3 and Data Recorder

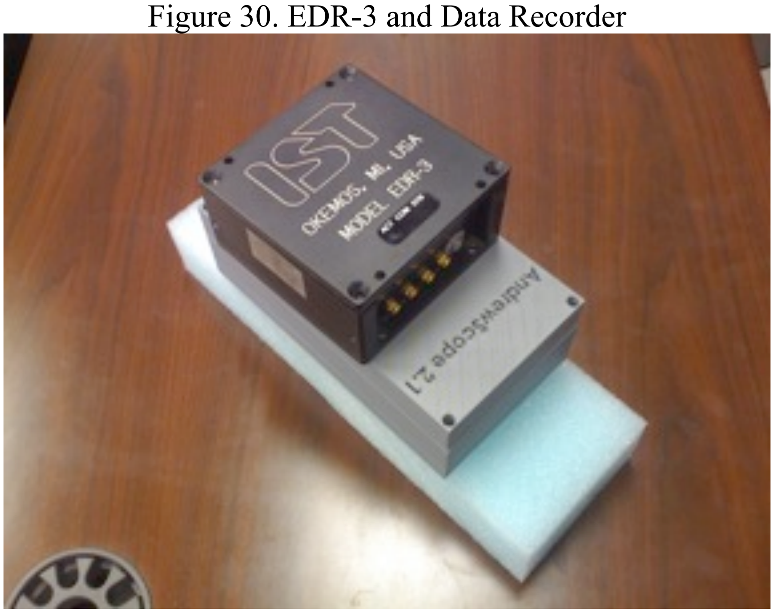

Figure 31. Both Recorders Placed in RSC

Test Plan

Eight data-recorders were designed and built for the study. The recorders were shipped to 7 different locations using 14 shipment routes, each repeated twice. Thus, a total of 28 segments were completed for each of the four box variables. Since there were four boxes, with 28 shipments for each box, the total number of shipments was 112.

Seven large-to-medium-size UPS hubs were chosen for their size, convenience and geographical distribution. Samples were randomly shipped to locations so that they would travel through each of the hubs at least four times. The UPS hub locations are listed and labeled in Table 2. Figure 32 illustrates the locations on a map of the continental United States.

Table 2. Shipment Locations and Codes

L	Louisville, KY
C	Columbia, SC
R	Rockville, MD
O	Ontario, CA
D	Dallas, TX
M	Miami, FL
P	Philadelphia, PA

Samples were shipped from Clemson, SC in groups of 8 (2 of each variable) and were mailed to a contact in the shipment locations (Table 3). All deliveries were made during the location's respective morning UPS delivery. Pick-ups for the next location also occurred at this same time. All codes used in the table refer to Table 2. Each time the samples were delivered, information from the data-recorder's memory card was removed, archived, and deleted from the memory of the card. If necessary, the batteries were replaced. After archiving the data, the unit was placed in the proper shipping orientation back into the box and mailed to the next location. When samples returned to Clemson, SC, the RSC was replaced and the unit was inspected for damage.

Table 3. Route Plan

Routes 1-8: Clemson → P → R → C → M → C → R → P → Clemson
Routes 9-14: Clemson → L → D → O → D → L → Clemson

Figure 32. Visual Diagram of UPS Hub Locations

Raw Data Treatment

Information taken from the data recorder was organized into a format designed to allow evaluation of the human compliance to the markings. Orientation, as characterized by an orientation number, was measured and recorded each second of time during transit. For example, if the package were resting with face 1 of the container upward for one minute, then the data recorder would have recorded 60 points corresponding to the number 1. If the package had been flipped 180 degrees after 30 seconds, then the data recorder would have recorded 30 points corresponding to the number 1 and 30 points corresponding to the number 3.

A program was coded into the microprocessor of the unit to consolidate the data prior to downloading to a computer. The average shipment contained over 500,000 data points, far too many to analyze. The program reviewed the data and counted the number of times the following events occurred:

1. A change in orientation that lasted between 0 and 3 seconds
2. A change in orientation that lasted between 3 and 20 seconds
3. A change in orientation that lasted between 20 seconds and 3600 seconds
4. A change in orientation the lasted greater than 3600 seconds

The rationale behind these groupings was to differentiate among the nature of the recording devices, non-human causes for wrong orientation, and direct human causes for wrong orientation. Group 1 relates to the device's natural response to certain inputs. Short impacts, drops, and exposure to the natural frequency of the package resulted in a change in the direction of gravity. Because the device is recording the relative position of gravity, when the package was in rebound, then gravity appeared to be reversed and the recorder marked this as disorientation. These instances only occurred and lasted from 1 to 3 seconds. They were noted in the qualification of the device and observed during shipping trials of the units.

Group 2 represented the time when the samples were inverted for longer than 3 seconds, but not more than 20 seconds. This grouping was chosen as prior research indicated that orientations lasting up to 20 seconds could be attributed to automated equipment in small parcel distribution centers (Singh, 2004). It can be assumed that these are non-human "re-orientations" of the package due to the nature of shipping facilities.

Groups 3 and 4 represented human errors, such as incorrect placement on a truck, at a dock, or at a residential address. These were recorded as improper orientations greater than 20 seconds. Because the modified labels used in the experiment dramatically reduced improper orientations within groups 3 and 4, it can be theorized that orientations lasting greater than 20 seconds are due to human errors, for automatic equipment would be unable to detect shipping labels.

The objective of this research was to determine if the color of the ASTM D5445-03 "This Side Up" symbol had an effect in reducing the total changes in orientations. Thus, the specific nature of the disorientation (i.e., which face was up) was not important.

The critical information was how often and for how long was the package oriented in an unwanted position.

Statistical Analysis

A statistical test for significance was used to properly analyze the recorded data. Because the data was organized into the occurrences of wrong orientations between 0-3 seconds, 3-20 seconds, 20-3600 seconds, and greater than 3600 seconds, it was first required to determine if the data recorded in these categories were significant. To begin, a null and an alternative hypothesis were constructed. The null hypothesis stated that if the means of the occurrences were statistically the same, then the data were not different from the control. The alternative hypothesis stated that at least one mean differed from the control. A separate test would then be completed if it was determined that a test's result was significantly different than the control.

A One-Way Analysis of Variance test was chosen to determine whether two or more sample means differed more than would be expected by chance. If it was determined that the data was statistically different, then a LSD test (least significance difference) was conducted to determine which sample varied most from the control.

CHAPTER 5

V. RESULTS AND DISCUSSION

Device Verification

Results of the eight ISTA 1G tests on the eight individual data recorders are shown in Figure 33. Analysis of the graph leads to the conclusion that the samples are able to record the proper orientation of the package throughout a rigorous dynamic environment and that the units record consistent data. Data was organized into scatter charts to easily view trends and changes in gravitational direction. The orientations of the panels are listed on the Y-axis, from 1-6. Time is shown on the X-axis and extends from 1-3600 seconds. The data show an average of 9 instances of changes in orientation lasting 1-3 seconds. Yet, each package only physically changed in orientation four times, as ISTA 1G requires. The apparent changes in orientation in this shortest time range must therefore be due to the bouncing of the package on the vibration table. When the package rebounded from a bounce, the device recorded this event as a change in orientation as gravity changed directions. The package was experiencing a form of shock being recorded by the device. Further programming would reveal the specific drop height of the package, but this information was not pertinent to the research. These rebounds can be filtered out and labeled as impacts and drops throughout the distribution environment.

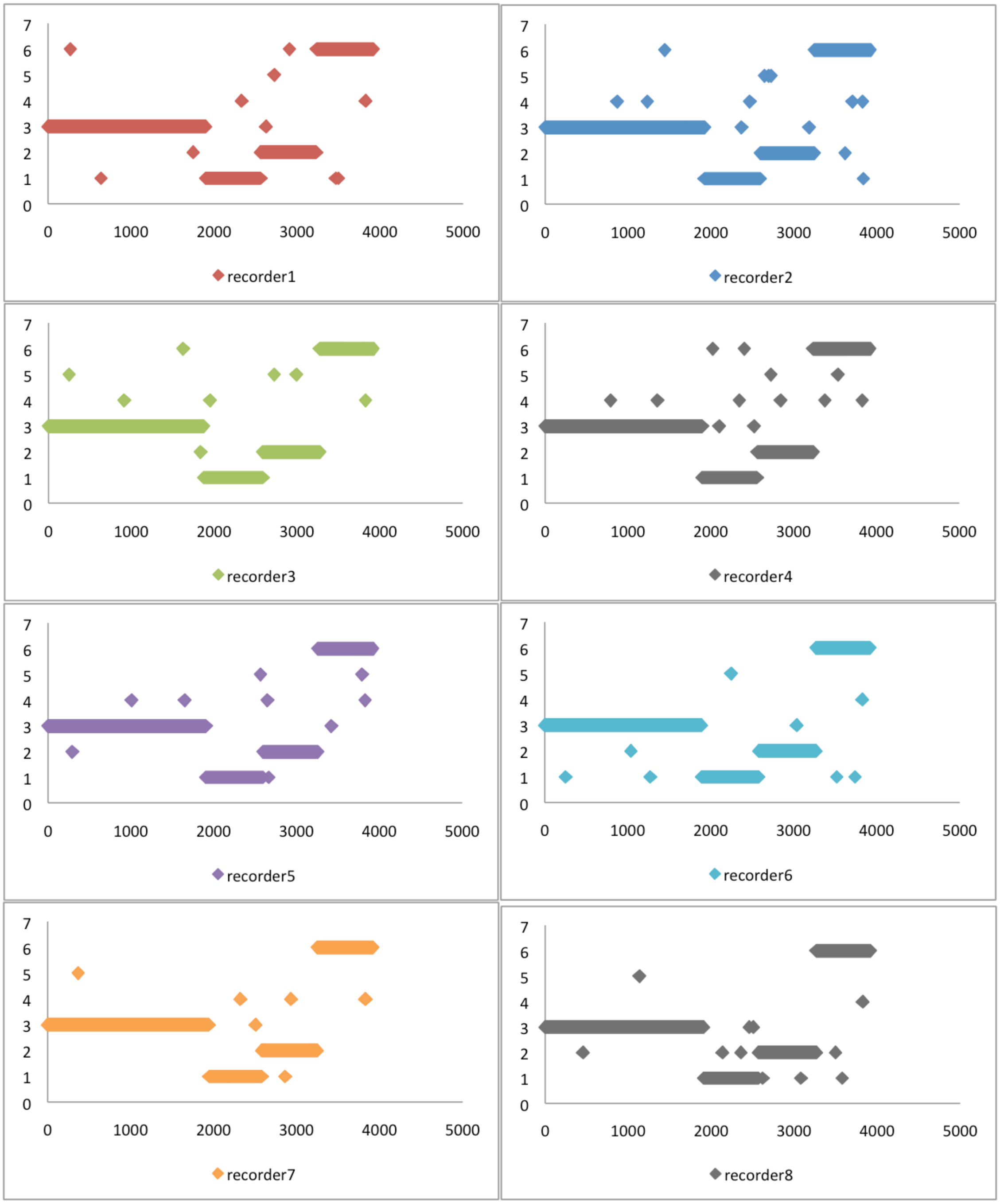

Figure 33. ISTA 1G Scatter Plots for Each Data Recorder

Table 4 illustrates the comparison of the data recorder built in this study and a commercial-grade accelerometer. For the commercial-grade accelerometer, due to the different programming, sensitivity, and calibration, values were recorded in lieu of gravitational force. Both units were able to assign the proper value to each axis when inverted on each panel demonstrating that the results are exactly the same. The EDR-3 unit required an actual shock, or event, to record data. The data recorder built for the research does not require an event to record data, as it is programmed to constantly record the position of the package.

Table 4. EDR-3 Vs. Data Recorder

Panel	**AndrewScope**			**EDR-3**		
	x	Y	z	x	Y	z
1	0	0	1	0	0	1
2	0	1	0	0	1	0
3	-1	0	0	-1	0	0
4	0	-1	0	0	-1	0
5	1	0	0	1	0	0
6	0	0	-1	0	0	-1

Prior to testing, the device was mailed throughout the U.S. to observe orientation trends and further qualify the device. As discussed above, changes in orientation fall primarily in four categories: between 0-3 seconds, 3-20 seconds, 20-3600 seconds, and greater than 3600 seconds. It was also determined that the battery power was not adequate for the shipments. Therefore, the Visual Basic code was changed to only record detected changes in orientation, rather than record the current orientation every second.

This change allowed the device to record for longer time periods and assisted with data analysis.

Label Experiment

A one-way ANOVA test was conducted for each orientation time frame recorded. All occurrences of undesired orientation were totaled for each of the four time frames to determine significance. If an F value was calculated to be less than the critical value (3.01) it was determined that the value was not significant. The F values and significance statements are in Table 4.

Table 5. ANOVA Results for Each Time Frame

Length of change in orientation	**F-value**	**Significant?**
0-3 seconds	0.69	No
3-20 seconds	2.60	No
20-3600 seconds	17.68	Yes
>3600 seconds	12.01	Yes

It was found that the wrong orientations for the four different label variations significantly differed from each other between 20 and 3600 seconds and greater than 3600 seconds. It was therefore concluded that the symbols had no effect over orientation changes between 0 to 3 seconds and 3 to 20 seconds. This observation is consistent with the characterization of the data in these time intervals. It was previously noted that changes in orientation from 0-3 seconds were most likely due to drops and rebounds rather than human handling. Most likely, these are sudden impacts recorded by the UPS trucks. Data from 3-20 seconds was not significant as these short-term disruptions in orientation are most likely the cause of automated equipment in the distribution centers. Singh also recorded this short-term phenomenon in a similar analysis of testing the effectiveness of “Do Not Drop” symbols (Singh 2004)

To determine which variable(s) differed from the control, a Fisher LSD test was completed for the time frames of 20-3600 seconds and >3600 seconds. Table 5 shows the results of the Fisher LSD test.

Table 6. LSD Test for 20-3600 Seconds

Hypothesis	**Point Estimate**	**LSD Value**	**Decision**
Ho:=μ_1-μ_2=0	0.11	0.9451	Fail to reject Ho
Ho:=μ_1-μ_3=0	1.61	0.9451	Reject Ho
Ho:=μ_1-μ_4=0	3	0.9451	Reject Ho

Conclusion 1): There is not sufficient evidence to suggest that the mean number of occurrences for 20sec-1h for variables 1 (control) and 2 (ASTM black) are different using a significance level of 0.05.

Conclusion 2): There is sufficient evidence to suggest that the mean number of occurrences for 20sec-1h for variables 1 and 3 (blue) are different using a significance level of 0.05.

Conclusion 3): There is sufficient evidence to suggest that the mean number of occurrences for 20sec-1h for variables 1 and 4 (black and white) are different using a significance level of 0.05.

An analysis of incorrect orientations between 20 and 3600 seconds indicated that the blue variable and the “black and white” variable differed from the control. Using the point estimates, it is clear that there is nearly no difference between the ASTM standard and the control. The ASTM standard only differed by 11.6% in effectiveness to the control. The modified blue symbol was 1.7 times more effective than the control. Since the LSD value is over 100%, the hypothesis is rejected.. The modified “black and white” symbol was 3 times more effective than the control.

Table 7. LSD test for >3600 Seconds

Hypothesis	**Point Estimate**	**LSD Value**	**Decision**
Ho:=μ_1-μ_2=0	0.18	0.694	Fail to reject Ho
Ho:=μ_1-μ_3=0	0.11	0.694	Fail to reject Ho
Ho:=μ_1-μ_4=0	0.68	0.694	Reject Ho

Conclusion 1): There is not sufficient evidence to suggest that the mean number of occurrences for >1h for variables 1 and 2 are different using a significance level of 0.05.

Conclusion 2): There is not sufficient evidence to suggest that the mean number of occurrences for >1h for variables 1 and 3 are different using a significance level of 0.05.

Conclusion 3): There is sufficient evidence to suggest that the mean number of occurrences for >1h for variables 1 and 4 are different using a significance level of 0.05.

An analysis of incorrect orientations that occurred for greater than 3600 seconds suggested that only the modified “black and white” symbol differed from the control. The modified “black and white” symbol was 2.5 times more effective than the control. It can be concluded with a 95% significance level that using a “black and white” ASTM “This Side Up” symbol reduced undesired orientations that occur for greater than 3600 seconds.

CHAPTER 6

VI. CONCLUSIONS

A data recorder was designed and built that recorded package orientation over time. The device qualified against a commercial accelerometer through an ISTA 1G test. The device is easy to use, accessible without tools, and may be analyzed in Microsoft Excel without file conversion.

The device was used in an experiment to determine if the current ASTM D4554-03 "This Side Up" pictorial marking was effective in communicating the correct package orientation to the package handler. The ASTM symbol was used along with a modified blue complement, a "black and white" contrast, and a control with no symbol. After a series of distribution tests throughout the country, it was determined the ASTM symbol did not perform differently from the control. In no instance was the ASTM symbol more effective in reducing improper package orientation over using no symbol at all. It was also determined that the use of contrasting colors increased the noticeability of the symbol; the modified symbols were inverted significantly less than the control. For inversions lasting longer than 1 hour, the "black and white" symbol was observed to reduce total incorrect orientation by 2.5 times over the control. The use of a complementary blue symbol reduced improper orientations 1.7 times more than the control for inversions between 20 seconds and one hour, where the "black and white" symbol reduced improper orientations 3 times more than the control.

Because the label experiment introduced changes to an environment, the results were reviewed for indications of the Hawthorne effect. The Hawthorne effect postulates that changes to an environment, no matter the nature of the change or the consequence of the change, result in equal increases of productivity. However, in the present label experiment, the symbol changes did not result in equal increases of productivity and noticeability. It was found that the “black and white” modified symbol was more effective than the modified blue symbol. Yet, if the results were due to the Hawthorne effect, these symbol modifications should have been statistically the same. Therefore, the results cannot be assumed to be short-term and due to the Hawthorne effect.

CHAPTER 7

VII. FUTURE RESEARCH

Future research based on the results of this study could lead into the development of a new symbol template to replace current ASTM D5445 pictorial markings. Because the research clearly illustrates the effectiveness of design theory on package handling, more studies should be conducted on additional concepts. Testing ideas such as double-complementary color schemes, the organic design of the Fibonacci sequence, and the principles of the von Restorff effect could produce interesting results. These principles would enhance the development of standards for international distribution symbols.

Another concept could involve informing the handler of improper treatment of the package. Audio warnings or printed electronics integrated into the design of symbols could notify the handler to correct a change or display the real-time number of unfavorable orientations. This research may show an even greater reduction of improper package handling.

APPENDICES

Appendix A

Raw Shipment Results

Table 8. Clemson to Miami

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	23	26	25	24	27	22	28	28
3-20 seconds	20	19	18	15	20	20	15	16
20-3600 seconds	5	6	2	7	3	2	2	2
>3600 seconds	3	5	2	4	1	2	1	1

Table 9. Miami to Columbia

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	20	28	29	29	28	25	26	20
3-20 seconds	16	19	20	15	17	16	17	17
20-3600 seconds	4	3	4	3	2	3	2	2
>3600 seconds	3	4	1	3	4	4	1	0

Table 10. Columbia to Rockville

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	25	22	24	25	27	27	27	27
3-20 seconds	20	20	12	17	18	15	18	17
20-3600 seconds	7	4	1	8	3	2	2	3
>3600 seconds	2	2	2	5	4	2	2	1

Table 11. Rockville to Philadelphia

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	25	27	28	27	24	27	25	25
3-20 seconds	17	19	19	20	19	18	15	16
20-3600 seconds	10	8	5	4	2	1	3	2
>3600 seconds	3	2	2	5	3	2	2	1

Table 12. Philadelphia to Rockville

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	21	25	27	25	25	28	26	25
3-20 seconds	15	20	20	21	14	16	17	17
20-3600 seconds	8	6	6	2	3	3	3	2
>3600 seconds	2	1	5	5	5	3	3	2

Table 13. Rockville to Columbia

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	28	29	25	31	25	26	24	26
3-20 seconds	16	18	19	17	17	15	18	16
20-3600 seconds	7	7	10	5	5	7	2	1
>3600 seconds	2	2	2	2	2	1	1	2

Table 14. Columbia to Miami

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	23	30	21	26	27	28	29	29
3-20 seconds	17	19	19	19	19	18	20	16
20-3600 seconds	6	8	7	9	6	5	2	3
>3600 seconds	5	5	4	3	3	3	2	2

Table 15. Miami to Clemson

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	30	25	27	28	27	24	28	25
3-20 seconds	20	16	15	14	16	17	16	18
20-3600 seconds	3	2	5	5	2	3	2	2
>3600 seconds	1	4	1	3	3	1	0	1

Table 16. Clemson to Louisville

Variable	**Control**		**Variable 2**		**Variable 3**		**Variable 4**	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	23	21	21	26	28	27	27	29
3-20 seconds	20	18	18	18	15	19	16	18
20-3600 seconds	5	2	7	5	6	4	4	2
>3600 seconds	3	1	4	2	2	2	2	2

Table 17. Louisville to Dallas

Variable	**Control**		**Variable 2**		**Variable 3**		**Variable 4**	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	28	23	23	25	26	25	27	27
3-20 seconds	15	17	20	12	16	20	13	18
20-3600 seconds	5	5	9	2	3	4	2	3
>3600 seconds	5	2	1	2	5	2	2	0

Table 18. Dallas to Ontario

Variable	**Control**		**Variable 2**		**Variable 3**		**Variable 4**	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	28	32	29	27	28	30	22	24
3-20 seconds	20	15	15	18	17	15	14	15
20-3600 seconds	6	3	8	7	5	4	0	3
>3600 seconds	3	2	5	5	5	4	1	2

Table 19. Ontario to Dallas

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	31	27	28	27	28	29	27	26
3-20 seconds	19	22	20	15	15	17	15	20
20-3600 seconds	6	5	7	3	5	4	3	4
>3600 seconds	5	3	5	4	2	3	0	1

Table 20. Dallas to Louisville

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	28	25	25	30	27	27	25	27
3-20 seconds	18	15	15	17	13	19	15	16
20-3600 seconds	3	4	2	3	4	3	1	2
>3600 seconds	4	1	0	2	2	1	1	1

Table 21. Louisville to Clemson

Variable	Control		Variable 2		Variable 3		Variable 4	
Shipment	1	2	1	2	1	2	1	2
Length of Change in Orientation								
0-3 seconds	25	22	27	27	29	25	28	29
3-20 seconds	18	18	19	20	17	19	19	17
20-3600 seconds	4	5	4	4	5	3	2	2
>3600 seconds	4	3	6	2	6	2	1	0

Table 22. Wrong orientation occurrences between 0-3 seconds for samples shipped

	Control	Variable 2	Variable 3	Variable 4	Shipment #
0-3sec	23	25	27	28	1
	20	29	28	26	2
	25	24	27	27	3
	25	28	24	25	4
	21	27	25	26	5
	28	25	25	24	6
	23	21	27	29	7
	30	27	27	28	8
	23	21	28	27	9
	28	23	26	27	10
	28	29	28	22	11
	31	28	28	27	12
	28	25	27	25	13
	25	27	29	28	14
	26	24	22	28	15
	28	29	25	20	16
	22	25	27	27	17
	27	27	27	25	18
	25	25	28	25	19
	29	31	26	26	20
	30	26	28	29	21
	25	28	24	25	22
	21	26	27	29	23
	23	25	25	27	24
	32	27	30	24	25
	27	27	29	26	26
	25	30	27	27	27
	22	27	25	29	28
mean	25.71	26.29	26.64	26.29	
st-dev	3.23	2.42	1.77	2.12	
variance	10.43	5.84	3.13	4.51	
max	32	31	30	29	
min	20	21	22	20	
s^2w	5.98				
s^2b	4.14				
$F = s^2b/s^2w$	0.69				

Table 23. Wrong orientation occurrences between 3-20 seconds for all samples shipped

	Control	Variable 2	Variable 3	Variable 4	Shipment #
3-20sec	20	18	20	15	1
	16	20	17	17	2
	20	12	18	18	3
	17	19	19	15	4
	15	20	14	17	5
	16	19	17	18	6
	17	19	19	20	7
	20	15	16	16	8
	20	18	15	16	9
	15	20	16	13	10
	20	15	17	14	11
	19	20	15	15	12
	18	15	13	15	13
	18	19	17	19	14
	19	15	20	16	15
	19	15	16	17	16
	20	17	15	17	17
	19	20	18	16	18
	20	21	16	17	19
	18	17	15	16	20
	19	19	18	16	21
	16	14	17	18	22
	18	18	19	18	23
	17	12	20	18	24
	15	18	15	15	25
	22	15	17	20	26
	15	17	19	16	27
	18	20	19	17	28
mean	18.07	17.39	17.04	16.61	
st-dev	1.92	2.53	1.91	1.66	
variance	3.70	6.40	3.67	2.77	
max	22	21	20	20	
min	15	12	13	13	
s^2w	4.13				
s^2b	10.75				
$F = s^2b/s^2w$	2.60				

Table 24. Wrong orientation occurrences between 20-3600 seconds for samples shipped

	Control	**Variable 2**	**Variable 3**	**Variable 4**	**Shipment #**
20sec- 1h	5	2	3	2	1
	4	4	2	2	2
	7	1	3	2	3
	10	5	2	3	4
	8	6	3	3	5
	7	10	5	2	6
	6	7	6	2	7
	3	5	2	2	8
	5	7	6	4	9
	5	9	3	2	10
	6	8	5	0	11
	6	7	5	3	12
	3	2	4	1	13
	4	4	5	2	14
	6	7	2	2	15
	3	3	3	2	16
	4	8	2	3	17
	8	4	1	2	18
	6	2	3	2	19
	7	5	7	1	20
	8	9	5	3	21
	2	5	3	2	22
	2	5	4	2	23
	5	2	4	3	24
	3	7	4	3	25
	5	3	4	4	26
	4	3	3	2	27
	5	4	3	2	28
mean	5.25	5.14	3.64	2.25	
st-dev	1.97	2.46	1.45	0.84	
variance	3.90	6.05	2.09	0.71	
max	10	10	7	4	
min	2	1	1	0	
s^2w	3.19				
s^2b	56.36				
$F= s^2b/s^2w$	17.68				

Table 25. Wrong orientation occurrences between >3600 seconds for samples shipped

	Variable 1	Variable 2	Variable 3	Variable 4	Shipment #
>1h	3	2	1	1	1
	3	1	4	1	2
	2	2	4	2	3
	3	2	3	2	4
	2	5	5	3	5
	2	2	2	1	6
	5	4	3	2	7
	1	1	3	0	8
	3	4	2	2	9
	5	1	5	2	10
	3	5	5	1	11
	5	5	2	0	12
	4	0	2	1	13
	4	6	6	1	14
	5	4	2	1	15
	4	3	4	0	16
	2	5	2	1	17
	2	5	2	1	18
	1	5	3	2	19
	2	2	1	2	20
	5	3	3	2	21
	4	3	1	1	22
	1	2	2	2	23
	2	2	2	0	24
	2	5	4	2	25
	3	4	3	1	26
	1	2	1	1	27
	3	2	2	0	28
mean	2.93	3.11	2.82	1.25	
st-dev	1.33	1.62	1.36	0.80	
variance	1.77	2.62	1.86	0.64	
max	5	6	6	3	
min	1	0	1	0	
s^2w	1.72				
s^2b	20.68				
$F= s^2b/s^2w$	12.01				

Appendix B

Visual Basic2® Program Code

```
'   {$STAMP BS2}
'   {$PBASIC 2.5}

' -----[ I/O Definitions ]---------------------------------------------
----

Dio             PIN     15                        ' data to/from module
Clk             PIN     14                        ' clock output
CS              PIN     13                        ' active-low chip
select
SPin            PIN     12                        ' serial out for SD
reader


' -----[ Constants ]---------------------------------------------------
----

XAxis           CON     0                         ' adcchannels
YAxis           CON     1
ZAxis           CON     2
VRef            CON     3

Cnt2Mv          CON     $CE4C                     ' counts to millivolts
                                                  '   0.80586 with **
GfCnv           CON     $3852                     ' g-force conversion

T1200           CON     813
T2400           CON     396
T9600           CON     84
T19K2CON     32
T38K4CON     6
Inverted        CON     $4000
Open            CON     $8000

Pacing          CON     30
Baud            CON     T19K2 + Inverted
ERROR_EOF       CON     7

' -----[ Variables ]---------------------------------------------------
----

axis            VAR     Nib                       ' axis selection
rvCount         VAR     Word                      ' ref voltage adc
counts
axCount         VAR     Word                      ' axis voltage adc
```

```
counts
mVolts          VAR     Word                    ' millivolts
gForce          VAR     Word                    ' axis g-force

dValue          VAR     Word                    ' display value
dPad            VAR     Nib                     ' display pad

counter         VAR     Word
value           VAR     Word
result          VAR     Byte
char            VAR     Byte

Or_Side         VAR     Word                    'storage for the side
position
loopcounter     VAR     Word                    'Counts the number of
times the program has gone through the main loop
extraloop       VAR     Word                    'extra numbers for the
loopcounter



' -----[ Initialization ]-----------------------------------------------
----
Main:

IF(loopcounter = 50000) THEN
extraloop =  extraloop + 1
loopcounter = 0
  ENDIF

  FOR axis = XAxis TO ZAxis                     ' loop through each
axis
    GOSUB Get_H48C                              ' read vRef& axis
counts

dValue = rvCount                            ' display vRef count

dValue = axCount                            ' display axis count

    IF (axis = ZAxis) THEN                      ' Side Z orientation 1
IF(axCount> 2400) THEN
IF(axCount< 2550) THEN
          DEBUG "side Z"
Or_Side = 1
          GOSUB Write_Data
        ENDIF
      ENDIF
    ENDIF

    IF (axis = ZAxis) THEN                      ' Side -Z orientation 2
IF(axCount> 1550) THEN
IF(axCount< 1700) THEN
          DEBUG "side -Z", CR
Or_Side = 2
```

```
          GOSUB Write_Data
        ENDIF
      ENDIF
    ENDIF


    IF (axis = XAxis) THEN                      ' Side X orientation 3
IF(axCount> 2400) THEN
IF(axCount< 2550) THEN
          DEBUG "side X", CR
Or_Side = 3
          GOSUB Write_Data
        ENDIF
      ENDIF
    ENDIF

    IF (axis = XAxis) THEN                      ' Side -X orientation 4
IF(axCount> 1550) THEN
IF(axCount< 1700) THEN
          DEBUG "side -X", CR
Or_Side = 4
          GOSUB Write_Data
        ENDIF
      ENDIF
    ENDIF


     IF (axis = YAxis) THEN                     ' Side Y orientation 5
IF(axCount> 2400) THEN
IF(axCount< 2550) THEN
          DEBUG "side Y", CR
Or_Side = 5
          GOSUB Write_Data
        ENDIF
      ENDIF
    ENDIF

    ENDIF
  ELSE
    DEBUG DEC result, " DID NOT RECEIVE PACING VALUE FROM DATA
LOGGER.", CR
  ENDIF

' -----[ Subroutines ]----------------------------------------------------
----

' Reads VRef and selected H48C axis through an MCP3204 ADC
' -- pass axis (0 - 2) in "axis"
' -- returns reference voltage counts in "rvCount"
' -- returns axis voltage counts in "axCounts"

Get_H48C:
  LOW CS
  SHIFTOUT Dio, Clk, MSBFIRST, [%11\2, VRef\3]  ' select vref register
```

```
SHIFTIN  Dio, Clk, MSBPOST, [rvCount\13]      ' read ref voltage counts
  HIGH CS
  PAUSE 1
  LOW CS
  SHIFTOUT Dio, Clk, MSBFIRST, [%11\2, axis\3]  ' select axis
SHIFTIN  Dio, Clk, MSBPOST, [axCount\13]      ' read axis voltage
counts
  HIGH CS
  RETURN

' ---------------------------------------------------------------------
----

' Right-justify value in 5-digit field
' -- move cursor first, then call with value in "dValue"

RJ_Print:
  LOOKDOWN dValue, >=[10000, 1000, 100, 10, 0], dPad
  DEBUG REP " "\dPad, DEC dValue
  RETURN

Done:
  DEBUG "Finished...", CR
  GOTO Finished

NoResponse:
  DEBUG "No Response From data logger.", CR

Finished:
  GOTO Finished

Write_data:

counter = counter + 1
    DEBUG "Appending ", DEC counter, " "
    SEROUT SPin, Baud, ["!AS", DEC Or_side, "                ", DEC
loopcounter + extraloop*50000, CR, LF]
    SERIN SPin, Baud, [result]
    DEBUG DEC result, CR
    PAUSE 1000
loopcounter = loopcounter + 1

    GOTO Main
```

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