Practical Aids for Teaching Experimental Designs

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1. INTRODUCTION

Design of experiments (DOE) is an essential tool for product and process improvement. Good software now makes the set up or design and analysis of experiments very easy, but many engineers and/or non-statisticians feel intimidated by statistical outputs. For that reason, non-statisticians need training in proper designing and conducting of experiments. Ideally the DOE training is best when provided on a just-in-time basis – prior to actually doing an experiment. However, an in-class experiment is a reasonable substitute for real-life experiments. It is important for technicians to gain an understanding of designed experiments so that mistakes made in conducting the experiment are reduced and the data is collected more correctly and accurately from the experiments. Managers read and possibly edit reports, and make decisions based on the experiments run by the technicians and engineers. An understanding of design and analyses techniques helps them identify any problems with the experiment or the results.

At SEMATECH, there are two general audiences. The first is comprised of project engineers. They are responsible for designing and conducting experiments to determine if the project they work on meets its goals. Most of them take eight days long course on designed experimentation that covers many basic concepts. The second group is comprised of project managers and technicians. This group does not have as great a need for the details of experimental design as the first group. Project managers manage the project engineers, and the technicians carry out the experimentation under the direction of the project engineers. The technicians also assist the project engineers in running the equipment on which the experiments are conducted. This **(what? What are you referring to when you say 'this'? Please explain.)** helps to ensure that experimental runs and data collection proceed smoothly. The project managers oversee all aspects of the experiment and must understand the outcomes of the experiments too. So the managers must provide adequate resources for the experiment, must know why certain designs are used, and be able to interpret and critique the analysis intelligently. The emphasis of the exercise is to motivate, illustrate, and provide hands on experience with the methodologies and analysis techniques discussed in class.

Need to include similar experiences from Stat-ease and Motorola.

2. EXPERIMENTS

2.1 Tabletop Hockey experiment

This hockey experiment is designed to illustrate the 2-level factorial experiment. It is a very simple and compact experiment, and most importantly, the results are not obvious to the experimenters. Instructors can provide students access to some commercial DOE software, such as the one given by Helseth (1997), to generate designs. With very little effort, they generate designs, which only reinforce discussions presented by the instructor. It can also generate a feeling of confidence among students. In case such software is unavailable, instructors can demonstrate students the use of random number tables or generators to develop randomization schemes. Most of the statistics books contain random number tables and most of the scientific calculators are capable of generating random numbers.

Setting up the Experiment:

The objective of the hockey experiment is to design and demonstrate a 2-level multifactor factorial experiment, such as 2^2 or 2^3 factorial experiment. The response to be measured is the distance the puck slides over a surface. The students work in teams of 4 with the following job functions:

- Referee #1: to drop puck
- Player: to shoot puck
- Referee #2: make measurement
- Reporter: to announce settings and record results

The materials required for this experiment are all readily available. Each team will need:

- 1 smooth-topped table, at least 6 ft in length.
- 1 hard plastic ruler, 6 in (15 cm) in length (such as Helix #11201) to use as the "stick". **Caution: even "unbreakable" rulers will break if bent too*

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far. For safety reason apply electrical tape for reinforcement.

- 4 quarters make a "puck" (pun intended).
- Gum-type adhesive (such as DAP Fun-Tak®) to stick the coins together.
- 1 six foot (2 m) tape measure (such as pocket Helix J01)
- The "player" may tire after taking several shots, so a fixture to hold the hockey stick ruler is recommended. This can be easily constructed out of wood by simply cutting a 1 cm deep slot.

Figure 1 shows a template that is provided to the students. It describes the dimensions of the optional fixture and other materials. Following factors are included in the experiment:

A. Shot type: "Slap" (set puck at "face-off" line, then retract and release stick) versus "Wrist" (set puck against fully retracted stick and fling it forward)
B. Stick length: "Short" (7 cm) versus "Long" (14 cm) as determined by the position of puck.
C. Windup: "Half" (2.5 cm) versus "Full "(4.5 cm) as determined by the distance the ruler is bent from its stationary position.

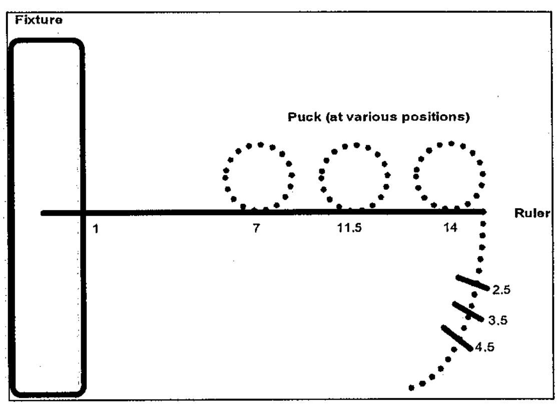

Figure 1: Template with pre-marked puck positions and stick setbacks

Encourage teams to brainstorm and come up with one or more additional factors. There is no limit to what students can choose to do as long as it is safe and reasonable. Remind them to keep in mind the time limit to complete the experiment while selecting additional factors. To maintain control, the instructor should pre-approve all DOEs. Some of the possible additional factors that can be studied are **[give a list of few possible factors... may be from those suggested by your students]**

The specific questions to be answered are:

1. What is the ideal setup for distance?
2. Are there any other factors that you think should be included in a comprehensive screening test?
3. What other responses could be measured?

During the discussion provide following tips for the data analysis:

- Be sure to check residuals - take appropriate remedial action
- Variability may make it hard to resolve effects - consider replication.

Experimental Procedure:

1. Clear equipment off the table to be used as a rink. *(Be careful: bend with knees not back!)*
2. Referee #1: Set "face-off" template at left corner of "rink" (must allow for right drift of wrist shot).
3. Referee #2: Insert "stick" in fixture with centimeter rule at top, with the "1" centimeter rule marking in the slot. Position it over spot marked on template.
4. Do some pre-trials to get a feel for the setup. *(Hint: test the extreme conditions to make sure puck won't fly into the stands.)*
5. All participants: Before beginning the experiment, develop a test plan including randomization scheme. Call the game off after 20 experimental runs. *(If you wish to deviate from this or any other suggestions, please ask for permission from the "commissioner" (your instructor)).*
6. Reporter: Reads off setup from test plan on computer.
7. Referee #1: Sets the puck (tails down) at the appropriate position on the template.
8. Player: Bends stick back to specified position using template as a guide.
9. Referee #1: If "slap" shot, leaves puck at face-off line. If "wrist" shot, sets puck against stick.
10. Player: Releases stick.
11. Referee #2: Measures distance from where the puck starts to where it stops.
12. Reporter: Records results in software.
13. All participants: Use software to analyze the data collected.

Typical Results:

Like any in-class experiment, results will vary, sometimes in a delightful way. For example, one team spread water on the table in an attempt to create a hydroplane effect. Almost every experiment reveals an unexpected interaction between shot type and stick length. One such example is described in Fig. 2.

The vertical bars in Fig. 2 represent least significant difference (LSD) intervals at 95 percent confidence level. As indicated by the overlapping intervals at the short end stick, there is no significant difference between two types of shots. The effect of stick length depends on the type of shot. The slap shot actually works better when the puck is set closer to the player, which is not intuitive.

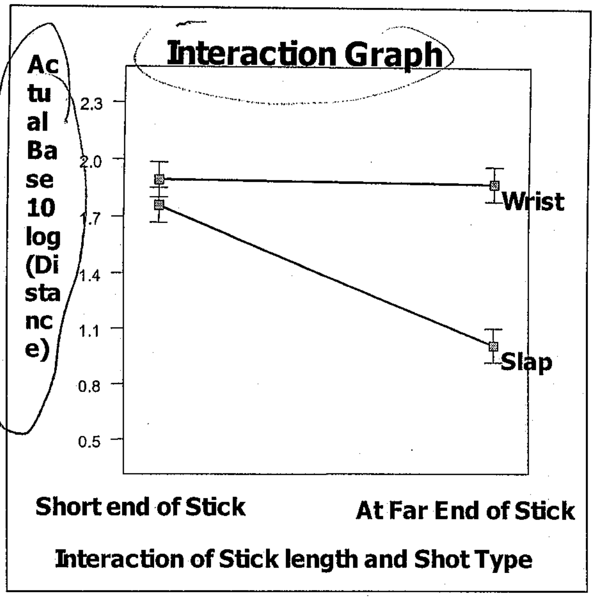

Figure 2: Typical Results from Hockey DOE

2.2 Paper Helicopter

The paper helicopter is becoming popular fast among the statistics teachers as one of the devices for teaching designed experimentation. It is also perhaps one of the widely documented experiments. While its exact origin is uncertain, one of the earliest publications comes from Rogers (1986). Since then, a number of works has appeared, including research reports from the University of Wisconsin's Center for Quality and Productivity Improvement (Box, 1991; Box & Liu, 1998), the organization with which most people associate the use of the paper helicopter. This proliferation of research is quite possibly due to the flexibility and potential of the helicopter as a curriculum aid. It has been shown useful in illustrating design types, such as full and fractional factorials (Box, 1991; Motorola University, 1997), split plot (Hazel & Lucas, 1997), and response surface methodology (Box & Liu, 1998), as well as design principles including path of steepest ascent, sequential experimentation, randomization, and blocking. Many instructors find it easy to develop conjectures on how physical characteristics of the helicopter affect its flight properties, without an understanding of aerodynamics or materials science. This is beneficial in an industrial setting, where audience members may have diverse educational backgrounds and experience levels.

Setting up the Experiment:

The exercise as described here involves a three factor full factorial. It can be easily extended to other designs. The response to be measured is flight time of the helicopter. It is defined as the time for which the helicopter remains in flight. The goal is to maximize flight time. Depending on class size, each class is broken into teams of 3 or 4 students each. Three functions to be performed by each team are:

- Dropper: Releases all helicopters from above his/her head while standing alone, on a step stool or a ladder. Dropper drops on timer's word.
- Timer: Starts timer when he/she instructs dropper to drop the helicopter. Stops timer when the helicopter hits floor.
- Recorder: Keeps track of the experimental plan and records flight time.

Allow each team to designate responsibilities among the teammates. Let each team decide randomization scheme, i.e., how the runs should be made (based on what is discussed prior to the exercise).

Materials needed to conduct this experiment are surprisingly few, inexpensive, and readily available.

- Paper is required to build the helicopters. Ordinary copier paper can be used, although one may wish to investigate the properties of different paper types.
- Scissors are required to cut out the shapes.
- A timing device is needed to record flight duration. Any digital stopwatch capable of measuring fraction of seconds such as ones used at the athletic events will suffice. They cost less than $10 a piece and are readily available at the sports equipment stores.
- If one wishes to ensure that experimental runs are made at a constant height, a tape measure and ladder may be employed. In the absence of tape measures, students can use some fixed marker such as top end of the doorframe to release the helicopter thereby ensuring constant distance traveled. By each helicopter.
- Optionally, a paper clip or other fastening device may be added as ballast.

The templates are shown in Fig. 3. Change the wing length/width and/or body length/width to get variations in the helicopter designs. Three factors considered in the experiment are described below. These factors are selected because they are known to produce a reasonable amount of variability in the responses.

ok!

Add figure 3 showing templates. Also give a website address where more templates are already available (or make them available) to download.

A. Wing Length: "long" versus "short" wings.
B. Body Width: "wide" versus "narrow" body.
C. Body Length: as measured by the number of bottom folds, "one fold" versus "two folds".

Generally instructor should provide the templates and allow students to cut, fold, and fly helicopters. If the instructor expects students to design and produce helicopters, preparation is limited to gathering the materials mentioned above. However, such open-ended design specifications will likely lead to spending too much time and focus on the physical design of the helicopter. This will be a distraction from the main intent of the course – teaching experimental (statistical) design. To limit the design step while allowing a reasonable amount of student input, it may be advantageous to restrict the investigation to a small number of helicopter characteristics. One may start with a generic template with fixed characteristics, limit the number of factors that may be investigated, and place restrictions on the magnitude of the changes. The specific questions to be answered are:

1. What is the ideal setup for distance?
2. Are there other factors that you think should be included in a comprehensive screening test?
3. What other responses could be measured?

Experimental Procedure:

1. Clear space of any obstacles. Paper helicopter travels vertically but sometimes tends to drift a little.
2. Prepare helicopters with different specifications. Cut along the solid lines and fold along the dotted lines.
3. <u>Dropper</u>: Climbs on the ladder/step stool. Marks the position from which each helicopter will be dropped. It can be a marker such as top of the doorframe.
4. <u>Recorder</u>: Selects appropriate helicopter according to the plan and hands it to the dropper.
5. <u>Recorder</u>: Calls out "start" and starts the timer.
6. <u>Dropper</u>: Drops the helicopter at the call from recorder.
7. <u>Recorder</u>: Stops timer as soon as the helicopter hits the floor. Records the flight time.

In the analyses, focus on graphical techniques such as dot plots, effects plots, cube plots, main effect graphs and interaction graphs. In the numerical analyses include hand calculations of effects. Demonstrate the calculation and interpretation of prediction equations and ANOVA tables. Finally, discuss results and methodology.

[Potential problems, strengths & weaknesses (specific) Pat, can you add something here?]

For more advanced class, this experiment can be extended to include fractional factorial, d-optimal, and response surfaces, where students would be expected to make use of sequential experimentation, randomization, replication, and path of steepest ascent. The design phase would be open ended, although they would be given a list of factors that have been considered by others. For examples refer to Box & Liu, 1998. Additional factors are shown in Table 1. Likewise, make available some of the analysis techniques covered in previous classes. Expect the use of computer at the designing stage if available for students.

Table 1: Additional Factors

Factor	Settings
Bottom Fold Position	Backward/Forward
Paper Clip	No/Yes
Paper Type	Copier/Construction
Gull Wing	No/Yes
Wing End	No Downturn/Downturn
Wing Mid-fold	No/Yes
Wing Trailing Edge	No Fold/Fold
Wing Leading Edge	No Fold/Fold
Corner Trailing Edge	No Fold/Fold
Corner Leading Edge	No Fold/Fold

2.3 The Roman Catapult

Many companies such as Texas Instruments, John Deere, Technicomp, and Lightening Calculator use roman catapult popularly to teach DOE (Santy and Einwalter (1997), and Trutna (1998)).

In 1988, Rod Walker, who was the Quality Manager for the Data Systems group at Texas Instruments, suggested use of the catapult as a tool to demonstrate the power of DOE. With the help of technicians a catapult was developed at TI. Ledi Trutna and Steve Schmidt started using catapult at TI to teach DOE and SPC classes. The scientists at Technicomp also built their own catapult for employee training. The scientists at John Deere modeled their own catapult after the Technicomp catapult but modified it to allow easier transitions between levels of each factor. Although based on the same principals, there are individual differences among these catapults, for example, the TI catapult uses balls whereas the John Deere catapult uses 2-in square custom-made bean bags.

The catapult can be used to demonstrate a wide variety of designs from a very basic 2X2 factorial experiment to the higher order factional factorial experiments. One of the reasons for their popularity being restricted to big industries is that they are fairly expensive. They can cost anywhere from $200 to $1,000 per catapult to construct. The cost can vary depending on the number of factors levels that can be accommodated as well as the nature of fine tuning in different levels that can be attained.

Setting up the Experiment:

This experiment can be set up to achieve one of two goals. One goal can be to optimize settings to achieve the maximum distance the ball/bean bag can be thrown. Alternatively, the experiment can be designed to achieve some preset arbitrary distance, say 100 in. The second goal is equivalent to many business situations and is favored more by engineers and managers. The response to be measured is the distance the bag or the ball is thrown. Every instructor using this experiment should emphasize safety and insist that students wear safety glasses. Again using teams of size 4 or 5 with following job assignments is suggested.

- Launcher: To position the ball/bag on the catapult and throw it
- Adjuster: To adjust different settings on the roman catapult for each run.
- Measurers (1 or 2): To measure the distance and determine if the target has been hit
- Data recorder: To keep track of the sequence of runs, and record the data.

The materials needed for this experiment are inexpensive and readily available. Each team will need:

- Catapult: Capable of adjusting different factors at different levels, such as the stop angle of catapult arm, catapult arm length, position of catapult, force applied for ejection, number of rubber bands used, etc.
- Payload: Something similar to small balls or beanbags. Exercise caution while selecting the payload. Choose items that will not cause damage to property of harm to participants if hit by it accidentally.
- A supply of rubber bands.
- A Tape Measure to measure the distance.
- Randomization device.

Let participants brainstorm and determine how many factor-level combinations should be used in the experiment. Instructor can lead the discussion towards a 2X2 factorial for the beginning students and use some other designs as the class progresses. Here the experiment is described using the stop angle and the arm length.

A. Stop Angle: Select two angles to position the catapult arm before releasing payload. Let us call them angle-1 and angle-2.

B. Arm Length: The cup position on the catapult arm can be adjusted to determine the arm length. Select two positions giving two lengths for the experiment, say length-1 and length-2.

Let students plan the experiment before collecting the data. Document the procedure used and brainstorm what might go wrong with the experiment. Help students determine how to design the experiment to take care of some of the things that could go wrong. At the same time help them understand that it is not possible to control everything, variation is natural part of the experimentation, and statisticians make efforts to understand the reasons for different variations.

Specific questions to be answered are:

1. What are the optimal settings to meet or exceed the goals for quality?
2. Did you achieve the goal within the time allowed?
3. Every throw costs money if it does not hit the target. Did you achieve the goal within the budget set by the management?

Experimental Procedure:

1. Clear tables and space around them of any obstacles. Generally payload travels in a specific direction for a well-designed catapult.
2. Plan the experiment. List the order in which runs will be done using some randomization technique. Modern software, such as JMP are capable of generating plans for experiments.
3. Recorder: Call out the run to be done.
4. Adjuster: Adjust settings on the catapult as called by the recorder.
5. Launcher: Position the payload on the catapult cup and release.
6. Measurers: Measure the distance between the catapult and the point at which payload lands.
7. Data Recorder: Record the distance measured.

Analyze the data using graphical as well as numerical methods. Compute interaction plot to study possible interaction effect.

Typical Results:

Typically in this experiment some sort of interaction between the Stop angle and the Arm length shows up. It is more obvious if more than 2 levels of a factor are used. Keep reminding students about cost considerations. That is the first thing they tend to forget since no actual cost is involved in the classroom setting. It has some natural variability that relates to the real life industrial situations, such as the rubber bands wear out and break. No two catapults are exactly the same. There is between operator variation as well as within operator variation. The changing position of the payload in the cup by run adds to the variation in distances. It teaches participants to identify different kinds of variations, and how to measure and reduce variation in the system. Some other factors that can be used in the experiment are: Start angle of the catapult, number of rubber bands used, height of the rubber band on the catapult arm, payload size, release technique, position of clamp, etc.

2.4 Gummy Bears in Space

This activity can be described as a less sophisticated, and less expensive version of the roman catapult. It does not have ability to include as wide a variety of factors as the roman catapult. It also is less accurate in setting different levels of a factor and gives less accurate results. This lower accuracy is somewhat useful because it gives instructor a chance to lead discussion towards different factors contributing to the variation and measurement errors. This experiment was first recorded by Scheaffer, Gnanadesikan, Watkins, and Witmer (1996) as 'Gummy Bears in Space" and is very popular among my students. Mulekar (1988) described this activity for an introductory statistics class. This activity is described here using a 2X3 factorial experiment, but can be extended to include more factors or levels.

Setting up the Experiment:

Objective of this experiment is to teach factorial experiment with replication. To begin with, the experiment can be started as a 2X3 factorial and extended to include more factors and/or levels. In this activity emphasis is given on designing an experiment to study the effect of two different factors on the responses through one experiment instead of two experiments, demonstrating and identifying interaction effect, recognizing need for randomization, and replication. The response to be measured is the distance traveled by the gummy bear through the space. There are different ways in which this distance can be measured. Let students discuss how the experiment should be conducted. Help them come to an agreement as to how the distance will be measured, between which two points, etc. Lead the discussion towards other factors that might affect the outcome and how to reduce such effect. Usually through this discussion students start realizing need for replication and randomization, although they may not use these terms.

Divide the class into teams of sizes 4 or 5 students each. Let each team assign following jobs to the teammates.

- Loader/Launcher: To position the gummy bear on the launcher and send it in space.
- Holder: To keep the equipment steady
- Measurer(s): To measure the distance traveled
- Data recorder: To keep track of the sequence of runs, and record the data.

The materials needed for this experiment are inexpensive and readily available. Each team will need:

- A Gummy Bear. A small pack of gummy bears that costs less than a dollar at the corner convenience store contains more than enough Gummy bears for one class. unless they get eaten :)
- Rubber Bands to make a launcher.
- Two Popsicle sticks to make a launcher.
- A dowel to make a launcher (easily found in any hardware store).
- A Tape Measure to measure the distance traveled.
- Books to change the angle of the launching pad.
- A Launching pad. Cardboard bases used for carrying 24 cans of soft drink, soup or vegetable cans, and discarded by grocery stores are useful for this purpose. They are quite sturdy. Lids of the paper boxes can be used too. But they tend to be less sturdy and sag in the middle.
- A die, if available is useful for randomization. Otherwise, write Low-Front, Low-Back, Medium-Front, Medium-Back, High-Front, High-Back one on each of six pieces of paper. Fold and mix to use for random assignment of treatments.

Use rubber bands to hold two Popsicle sticks together at one end. Put a dowel between two Popsicle sticks close to the rubber band making sort of a V shape. This makes our launcher.

Start the experiment with two factors, namely, the angle of launching pad and the position of launcher on the launching pad.

A. The Angle: "Low" (three books under one end of the launching pad), "Medium" (five books under one end of the launching pad), and "High" (seven books under one end of the launching pad).
B. Position: "Front" versus "Back", as determined by the position of the launcher on the launching pad.

Let students discuss how the experiment should be conducted to determine the effect of the "angle" and the "position" on the distance traveled by the Gummy bear. Help students come to an agreement as to how the distance will be measured, between which two points, etc. Lead the discussion so that students will realize need for randomization and replication.

Specific questions to be answered are:

1. What is the ideal set-up for achieving maximum distance?
2. What is the nature of interaction between two factors, if any?
3. Did you encounter any difficulties during the experiment? How did you solve them? What effect might they have (if any) on the results?
4. Are there any factors other than the angle and the position affecting the results and need to be controlled?

Experimental Procedure:

1. Clear space of any obstacles. This experiment is best performed on the floor. If conducted on the tabletop, the bear may fly off the table making it somewhat difficult to measure the distance traveled.
2. Prepare launchers using 2 Popsicle sticks, a rubber band, and a dowel.
3. Prepare design of the experiment. List the order in which trials will be conducted using some device for randomization.
4. Recorder: Call out the trial to be conducted.
5. Loader/Launcher: Position the launcher on the launching pad as called out by the recorder.
6. Loader/Launcher: Press the Popsicle stick all the way down, put Gummy bear on it, and release pressure on the stick to let the Gummy bear travel through the space.
7. Measurer(s): Measure the distance traveled by the Gummy bear according to the predetermined criterion.
8. Data Recorder: Record the distance measured.

Use a table similar to Table 2 to record the data as it is collected.

Table 2. Data Recording Sheet

	ANGLE		
POSITION	Low	Medium	High
Front	1. ____	1. ____	1. ____
	2. ____	2. ____	2. ____
	3. ____	3. ____	3. ____
	4. ____	4. ____	4. ____
Back	1. ____	1. ____	1. ____
	2. ____	2. ____	2. ____
	3. ____	3. ____	3. ____
	4. ____	4. ____	4. ____

Start analysis by preparing the table of means as described by Table 3.

Table 3: Table of Means

	ANGLE		
POSITION	Low	Medium	High
Front	____	____	____
Back	____	____	____

Graph these means to get an interaction plot. Ask students to describe the pattern and help them interpret it.

Typical Results:

Interaction plots vary from group to group, but typically interaction emerges. Figure 3 shows results from one such group. Show graphs from all groups and discuss similarities and differences between the outcomes for different groups and possible reasons for them. Sometimes discussions reveal some unexpected events and how students handled it. For example, once a Gummy bear that one group received was somewhat dry. Halfway through the experiment it broke. So students realized that the resulting distance traveled would be affected if the payload (as they referred to the Gummy bear) changed during the experiment.

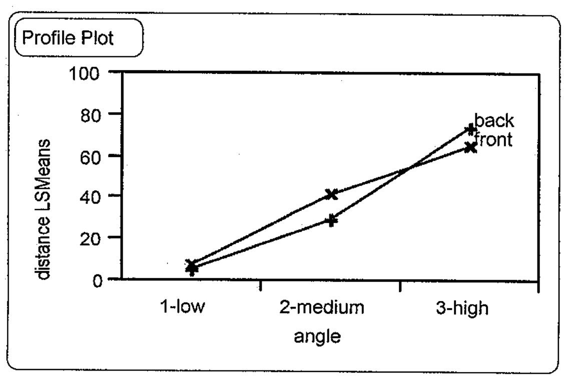

Figure 3: Interaction plot for Gummy bears

CONCLUSIONS

These experiments have been well received by adult learners from a variety of industries, as well as college students. Some of the advantages of these experiments are listed below. These features make them ideal in-class exercises for the DOE.

- All of these experiments are very simple. Students don't think that the instructors are trying to trick them.
- They are fun and appealing to participants.
- An experienced instructor can manage to lead the classroom discussion so that issues generated are related to the participant's real life experimental backgrounds at the work place.
- On the other hand, no knowledge of a specific discipline is required. So they can be used to address a group with mixed backgrounds.
- Materials needed are readily available and inexpensive for all experiments, except the catapult. But catapult, once built can be used without any recurring costs and will be cost effective for a long time.
- These experiments have ability to generate fruitful discussions about the factor choices, response choices, measurement methods, experimental protocol, measurement errors, etc.
- All the experiments are flexible enough to accommodate different number of factors and their levels.
- All the experiments can be used to demonstrate a wide verity of designs.
- They can be used almost anywhere. They are simple and compact for instructor to set-up and explain. They do not require a fixed laboratory setting and can be easily moved from room to room or even across the country.
- All the experiments are simple, and realistic. Therefore results are more believable.
- The results of the experiment generally surprise the students with an unexpected interaction, thereby making them interesting.
- All of them contain several sources of natural variability, which are useful for discussion purposes.

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