A Preliminary Study to Measure the Relationship of Lighting to Productivity on a Construction Project

Bruce W. Smith, CPC and C. Ben Farrow, P.E.
Auburn University
Auburn, Alabama

The profitability of a construction project for the general contractor and subcontractors is largely based on the estimation of the labor time. Labor time is based on the productivity of the worker. Although there are numerous variables that impact productivity, this study seeks to determine if the lighting levels impact productivity of construction workers. The study uses a controlled environment and a defined task under two different lighting conditions to measure productivity on a small, specific, construction related task of laying out the location for a metal stud partition. One light level was below the OSHA minimum requirement, and the other light level was above the OSHA requirement. Twenty-seven teams, each consisting of two construction management undergraduates, attempted to locate the partition under one of these lighting levels. Productivity was quantified by measuring the task time and accuracy. Results indicated a trend toward decreased time for teams under better lighting conditions, but increased errors were observed for groups operating in the higher light level. The large number of errors and the confidence interval of time required cast doubt on the study's attempt to quantify productivity. Further study is needed to remove the effects of the largely untrained labor force used.

KEY WORDS: Temporary Lighting, Construction, Productivity, Quality, Time

Introduction

Recent publications have indicated that many buildings under construction do not meet the minimum OSHA standard for illumination (Smith, August 2006: Smith & Azhar, 2007). The known hazard of the lighting condition is the impact on safety. The unknown result of the poor lighting condition is the impact on productivity as measured by both quality and speed. Linking improved lighting to increased productivity could provide the motivation for change. The challenge of linking productivity to lighting on a construction project lies in the number of variables and the inability to limit the variables in the construction environment. The current study is a preliminary investigation to examine the impact on lighting on the productivity of a specific construction task.

The preferred method of measuring productivity would be to perform an experiment in an actual working environment, and recording the output of workers over a long period of time. Manufacturing is able to conduct such studies because workers are in a controlled environment with the same workers performing repetitive tasks. However, productivity in the construction environment is especially difficult to measure since the environment for a building under construction is always changing. Weather is a constantly changing variable. Different light levels occur as the building moves from an open site to an erected structure without permanent lighting. Different sections of the building have varying accessibility issues. The presence of multiple trades complicates productivity as the work progresses. Construction has its share of repetitive tasks, but even the repetitive tasks vary. Multiple types of material are used for similar functions. Material is installed at different elevations above the floor making accessibility difficult. Designs differ from project to project, and the degree of difficulty varies tremendously. Finally, the work force is constantly changing. Different crews, different workers within crews, different levels of skill, and different levels of motivation may all work within a very confined area within a short period of time on a construction project. All of these issues yield different performance results with regard to speed and quality. The *Mechanical Estimating Manual* lists sixteen factors that can impact labor productivity in construction (D'Amelio 2006):

- Stacking of trades
- Morale and attitude
- Reassignment of manpower – change orders
- Crew size inefficiency – over manning
- Concurrent operations
- Dilution of supervision
- Learning curve
- Errors and omissions
- Beneficial occupancy
- Joint occupancy
- Site access
- Logistics
- Fatigue
- Ripple
- Overtime
- Season and weather change

Productivity is a function of the labor and capital that is invested in a task (OCED, 2001). Full efficiency in an engineering sense means that the production process has reached the maximum output with the current technology and fixed amount of inputs (OCED, 2001). Improved productivity is generally recognized in one of three ways. First, workers can work harder or longer at a given job. Second, companies can purchase better tools, equipment, systems, and technology to make work easier and faster. Finally, firms can rearrange the flow of work to make it easier and improve quality. This study's approach of improved site lighting fits within the concept of improving "equipment and systems" for workers.

Increasing productivity has multiple benefits for the construction industry. First, owners can purchase more for the same amount of money and increase return on investment.. Second, increase productivity can increase wages for workers raising living standards. Finally, construction companies become more efficient and more profitable. Throughout history, productivity has been a key driver for economic prosperity.

This study seeks to determine if an experimental environment could be created to determine whether there exists a link between two different light levels and the productivity of the assigned task. For this study, productivity was based on the time required to complete the task and the quality of the work. The light levels used in the study used one light level below the OSHA minimum standard for buildings under construction, and one level above the minimum OSHA standard. In order to limit the number of variables, the study was conducted in a controlled environment with a defined task performed by twenty-seven teams of workers. Workers were student volunteers currently enrolled as sophomores in a Construction Management curriculum. This paper provides a summary of previous studies on temporary site lighting, details the methodology used for this quantitative experiment, reports the results, and provides analysis and conclusions reached as a result of the work.

Background

Construction, like any other industry, is based on the maximization of productivity. The relationship of illumination in the workplace to quality and productivity is not a new concern for employers. The Hawthorne Experiments from 1924 to 1927 included illumination studies. The hypothesis was that greater illumination would generate higher productivity. Unfortunately, the studies were inconclusive because of the construction of the experiment (Ballantyne, 2000), but the study was a milestone by influencing future studies of productivity and environment.

More recently, the Light Right Consortium released the results of a field simulation that indicated a causal relationship between lighting quality and worker satisfaction and motivation (Dilouie, 2003). Although the simulation was conducted in an office environment, the relationship between lighting environment and worker motivation could possibly be applied to the construction process.

The link between illumination, quality of work, safety, and productivity provides the motivation to examine current conditions and the opportunity to look at methods of improving temporary lighting. This link is important, as any improvement in illumination would require the allocation of resources. The general contractor or owner would need to believe that the cost of the changes was returned in higher quality work and/or more productivity. The Light Right study identified the barriers to improved lighting as the initial cost and the lack of evidence that there is a link to performance. The study also found that 87% of the companies interviewed would spend the money if the return on investment could be demonstrated (Dilouie, 2003).

Broadly speaking, productivity measures can be single factor productivity measures or multi-factor productivity measures (OCED, 2001). In construction, major concerns are time and quality. Since tasks vary tremendously on the jobsite, it is difficult to obtain any reasonable measure of productivity by using a single factor productivity measure. For example, consider the simple task of locating a metal stud wall at several locations on just one job site. It would be difficult to obtain a meaningful productivity number based on a single factor such as time since the wall dimensions from room to room are different, metal stud sizes vary, door opening sizes and locations vary, etc… Thus, multi-factor productivity measures are more applicable for the construction industry.

The measurement of productivity and the assignment of productivity rates to specific tasks on a construction project are central to estimating the cost of a project. Construction companies use sources such as “Means Cost Estimator” and various software programs to estimate the cost to perform each task in the construction process. Estimators also use past experience of the company to get a more accurate prediction of the time to perform work. All estimating of labor is based on the productivity of the workers, which is an average productivity rate based on a large amount of historical data. The advantage of using the large data base is that the many variables are normalized, and the experienced estimator can factor in some of the variables that can be addressed, such as the impact of winter conditions.
The study of the impact of temporary construction lighting on productivity and quality is intrinsically subjective in nature. Each jobsite is unique and the workforce is always changing. The current study attempts to minimize the variables and look at temporary lighting objectively.

Methodology

The experiment attempted to limit the number of variables. The study was conducted in a building at night, so weather and light levels could be controlled. Participants were put in teams of two and asked to perform a relatively simple "lay-out" task, so the skill level to complete the task did not involve any work with tools, other than measurement and marking. The ability and motivation of the workers could not be controlled, so 28 teams were used in order to create a statistical comparison.

The experiment was designed to measure the difference in productivity for a construction task under differing light conditions. The location of the study was in a high bay lab so lighting, temperature, and interruption could be controlled. The area necessary for the testing was approximately thirty feet by thirty feet in the center of the room. There was enough space for two teams of participants to work at one time. The testing of two teams simultaneously allowed some freedom in scheduling, as it was not known how long it would take for a group to finish the task. The teams were separated to avoid collaboration on the task. Figure 1 shows the task the teams were asked to perform.

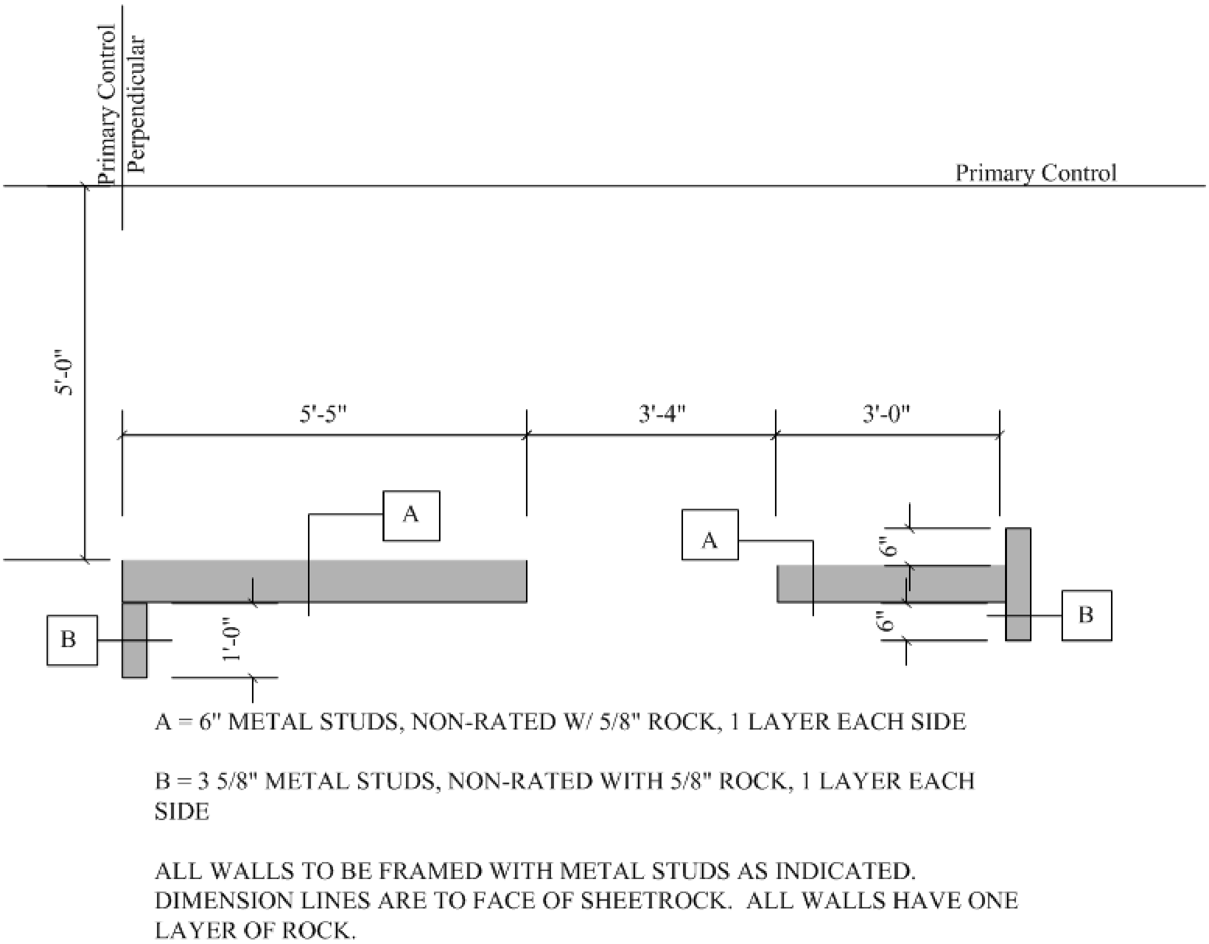


Figure 1: Sketch of Partition Wall to be Located in Productivity Study

The participants in the task were second year students in the construction management program who volunteered. There were two participants in each team. Each team was given a number that was used to identify the completed task. The team number was not linked to the individual participants, so there was no link between the outcomes to any participants.

The task the participants were asked to perform was to lay-out two “L” shaped walls. The participants were given directions and a sketch of the walls to be laid out. The drawing is shown in Figure 1. The participants were read the directions, so each team got the same information. The information was sufficient for the teams to perform the task.

The measurement of productivity was twofold. First, the teams were timed from after the instructions were given to the time the task was completed. The completed task was then evaluated for accuracy. The measurement for accuracy was not done until all the teams had completed, and the teams were not present for the measurements. There were ten reference points that were measured for accuracy. Each of the points was rated from one to ten for the accuracy based on deviation from the correct point. A rating of one indicated that there was no deviation. A rating of two indicated that the group had the second closest measurement to the correct value. Ratings for teams varied from as low as one to ten when the deviation depending on the team’s performance relative to others and the actual value. The points were chosen so that errors on one point would not show as an error on another point. The testing hypothesis was that the shortest time and the lowest number on the accuracy rating system would be the most productive.

The variable tested was the light level. The high light level was ten foot-candles (fc) as measured on the floor in the area where the task was being performed. Ten fc was chosen the high level as there was a noticeable difference in the illumination from the low light level, and ten fc provided a very comfortable level of light without going above a realistic level of illumination for a construction site. The high light level used the part of the permanent lights in the room, and included six thirty-two watt florescent bulbs. The low light level was two foot-candles. The low lighting used two 100 watt incandescent bulbs eleven feet above the floor, using standard temporary lighting fixtures with yellow plastic cages. The lights were located directly over the work areas for the testing. The low level if light at two fc was chosen because previous studies (Smith and Azhar, 2007) showed that two fc was at or above the illumination levels found on many jobsites analyzed, where natural light was not a factor.

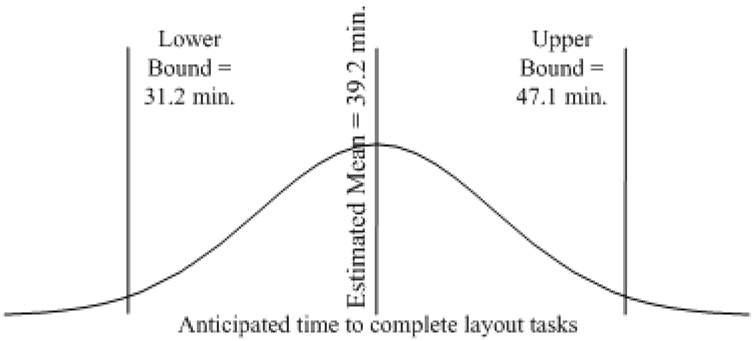
Twenty-seven tests were performed on three consecutive nights from 5 PM to 9 PM. Fifteen of the tests were at the high light level, and twelve were at the low light level. The light level was changed each evening, with part of the teams at each light level. The light level for the test was set before the teams entered the area. The participants were aware that lighting was different for different teams, but there was no other explanation about the purpose of the task.

Results

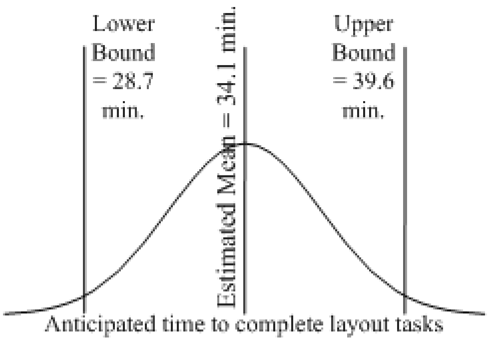
Results are detailed in Appendix A. Values shown in the appendix include group number, lighting level, time to complete the layout, and measured dimensions at each of the established ten reference points.

Measurements of time to complete the layout tasks indicated that teams who had higher levels of lighting completed the task faster than those with lower levels of lighting. On average, the groups assigned a low level of lighting completed the task in 39.2 minutes while the groups assigned a high level of lighting completed the task in 34.1 minutes. Of the fastest thirteen teams, nine of the thirteen (69%) operated under the higher light condition. The fastest performance in the low light category was the fourth fastest overall and a full nine minutes behind the fastest high light team.

If one assumes that the time to complete the assigned task can be approximated with a normal distribution then a confidence interval for time to complete the task can be developed. This interval estimate of time allows one to indicate the reliability of the estimated mean. Using a 95% confidence interval, the range of time for the low light condition is found to occur from approximately 31.2 minutes to 47.1 minutes (15.9 minute interval). Similarly, the range of time to layout the wall under high light conditions is anticipated to be between 28.7 minutes and 39.6 minutes (10.9 minute interval) (Figure 2).



95% Confidence Interval for Time
to Complete Low Light Layout



95% Confidence Interval for Time
to Complete High Light Layout

Figure 2: 95% Confidence Intervals for Low and High Lighting

Accuracy measures were taken relative to ten known reference points for the wall layout, and differences from the anticipated measurement and the actual measurement were determined for each group. An overall "accuracy ranking" was then established. Of the ten teams with the best accuracy, one-half (five teams) operated under low light conditions while the other half operated under high light conditions. The overall ranking for accuracy assigned to low light teams was 2.5 compared to a 3.2 value for high light teams. Such a result indicates that better accuracy on average was achieved by teams operating under a low light condition.

The average difference in measured and anticipated values was determined for each team and then averaged to compare low level lighting and high level lighting conditions. This comparison yielded a similar finding as the average error for low light teams was 0.46” while the high level lighting teams had an average error of 0.75”. These results compare favorably with the ranking scheme established.

No single team placed the wall in the correct location for all ten reference points. The best performing team had five reference points within 1/8” of the correct value with only one reference point 5/8” out of tolerance. The worst performing team had only two of the ten reference points in the correct location. Five of their ten points were out of tolerance by more than 1”.

In a typical manufacturing environment, quality control is often measured by the proportions of defects in a lot (P-chart system). P-charts are used to determine if the process is stable and predictable, as well as to monitor the effects of process improvement theories. Specifically, this approach addresses whether or not the quality is maintained within statistically acceptable upper and lower bounds of quality. Considering the process as a whole regardless of lighting levels, this approach was applied to help determine whether the quality control of our process was “in control” or “out of control”. Measurements were considered defective if the difference in expected and actual measurements exceeded 1/8”.

The average of all layout samples indicates an error of 0.357 or 35.7%. Once this average was established, an upper and lower bound for samples were computed using the following p-chart formula:

$$\bar{p} \pm 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

Such an approach yielded a lower bound of 8.0% and an upper bound of 63.3%. Of the twenty-seven total data points, two fell above the calculated upper bound. Such a result indicates that the process is “out of control” and modification to the process is necessary.

Finally, some interesting qualitative visual observations were observed for the teams operating under low-light conditions. First, the only groups that questioned or worked to improve their tools were groups under low-level lighting. These groups sometimes asked to sharpen their pencils or clarify the lines used for control points. No similar behavior was observed with the groups using the higher lighting levels. Second, only one of the group members of all teams disengaged from the exercise. This occurred with one group in a low lighting setting where the team member excused himself after approximately twenty minutes only to return late in the exercise.

Authors’ Analysis and Conclusions

The expected outcome of the study was that productivity in terms of both “time to complete the task” and “number of errors made” would be reduced using higher levels of light. This study indicated that the average time to complete the tasks was improved, but the high number of errors made in the layout by all teams discounted the initial value of this finding. It also significantly discounted the hypothesis that quality would improve significantly in high levels of lighting since actual results showed the contrary.

The width of the confidence interval for time to complete the task gives some idea about the uncertainty of the parameter of time. For the low-level light condition, this interval was 15.9 minutes. For the high-level light condition, this interval was 10.9 minutes. In the opinion of the authors, these confidence intervals are too high to establish reliability and to form any fundamental theorem of time to complete a layout task under varying light levels. It is interesting to note that the lower bound for the confidence interval in both lighting levels was similar (28.7 minutes to 31.2 minutes) while a larger difference existed in the upper bound (39.6 minutes to 47.1 minutes). From these results, one could infer that the effects of lighting may be magnified for exercises where the task is not clearly understood or where problems develop during the layout exercise. Further study is warranted to consider both average time and possible upper bound effects.

The result that errors were reduced under low lighting is difficult to explain. The authors' believe that such a result is primarily due to the use of students untrained in layout to perform the tasks. The learning curve for layout was so steep for the students that the errors they made were primarily due to their lack of experience in layout. This issue likely dominated the error matrix and prevented any reasonable attempt to define the effect of lighting on the exercise. Further studies must standardize the time required and limit the overall number of errors made due to items outside the "level of light" issue.

Another scenario not considered by the authors is that the low levels of lighting may yield more cautious thinking and planning than shown by the groups using high levels of light. If the teams visually recognize that lighting is minimal, and they are attempting to minimize layout error, they may subconsciously think more critically and plan more carefully how each segment of wall is to be placed. Such a result had not been considered as part of this research but would warrant consideration in any future productivity study.

In order to effectively measure productivity as defined in this paper, a method is necessary to develop some sort of overall index of productivity. Aggregating measurement systems of different units (time and number of defects) is difficult. Such an approach would allow combination of different measurement systems into a single system and allow productivity comparisons across different units. For example, output may need to be defined as the number of defect-free measurements made over a certain time period.

In summary, the authors believe that any study of lighting productivity on the job site should include both metrics of time and quality. Based on this preliminary study, there are indications that time to complete a layout task can be reduced with higher levels of lighting but further study is necessary. The authors recommend repeating the study using experienced trades people who will complete the task in a narrower time frame with a smaller number of errors. Such an approach will reduce the variability of the experiment and help reduce the key variable of "untrained" workers faced by this study.

References

Ballantyne, P.F. (2000). Hawthorne Research, *Readers Guide to the Social Sciences* [WWW document]. London: Fitzroy Dearborn, retrieved from the Web on 12/26/05 from URL http://www.comner.ca/~pballan/HAWTH.HTM

D'Amelio, J, (2006). *Mechanical Estimating Manual*. Atlanta: Fairmont Press.

Dilouie, C. (2003). Lighting and Productivity: Missing Link Found? [WWW document], *Architectural Lighting,* October 1, 2003, retrieved from the web on 12/26/07 from URL http://www.archlighting.com/industry-news.asp?articleID=453031&sectionID=0

Fields, A. and Hill, D. (2006). *Measuring Productivity and Evaluating Innovation in the U. S. Construction Industry*. Arlington, Virginia: Building Futures Council.

OCED (2001). Measuring Productivity. *OEDC Manual.* Organization for Economic Cooperation and Development.

OSHA Construction Industry Regulations 29 CFR 1926, updated through Jan 1, 2004. Davenport, Iowa: Mangan Communications, Inc.

Smith, B. W. (August 2006). Proceedings of Temporary Construction Lighting: A study of the requirements and the impact on the working environment, productivity, and the quality of work. *The World Conference on Accelerating Excellence in the Built environment*. Birmingham, UK.

Smith, B. W. and Azhar, S., PhD. (2007). Inadequate and Unsafe Temporary Lighting in Buildings under Construction: Risks, Challenges, and Solutions. *Presentation and Publication in the proceedings of Fourth International Conference on Construction in the 21st Century (CITC-IV) "Accelerating Innovation in Engineering, Management and Technology".* July 11-13, 2007, Gold Coast, Australia.

Appendix A
Lighting Productivity Study

	Accurate Dimensions	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results	Raw Results
Group		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Lighting Level		High	High	High	Low	Low	Low	Low	Low	Low	High	High	High	High	High	High	High	High	Low	Low	Low	Low	Low	Low	High	High	High	High
Time (min)		25	32	34	29	32	43	35	60	72	50	26	29	46	32	17	22	32	33	43	40	27	26	30	40	42	56	29
Accuracy (1)	*4.625*	4	4.375	4.625	4.625	4.625	4.625	4.625	4.625	4.625	4.625	4	4.625	4.625	4	4.5	4.25	4.625	4.625	4.625	4.625	4.625	4.625	4.625	4.5	5	4.625	5.25
Accuracy (2)	*4.625*	4	4.5	4.625	4.25	4.625	4.625	4.625	4.5	4.625	4.5	3.75	4.625	4.625	4	4	4.5	4	4.625	4.625	4.625	4.625	4.625	4.625	4.5	4.75	4.625	10.875
Accuracy (3)	*11.625*	11.5	12.125	11.625	11	11.5	11.625	11.5	10.875	11.625	10.25	11.625	11.125	11.5	10.25	6	11	13.5	11.5	13	11.375	11.5	11.5	11.5	11.5	11.5	11.625	13.375
Accuracy (4)	*6*	6	6	5	6	6	6	6	6	6.125	5.875	6	6	6	4.625	11.75	6	6	6	5.25	6	6	6	6	5.875	6	6.625	6.875
Accuracy (5)	*3.625*	3.5	3.625	3.625	3	3.5	3.625	3.5	3.125	3.625	3.625	3.375	3.625	3.625	3.5	3.625	3.5	6	3.5	3.5	3.5	3.375	3.75	3.625	3.5	3.75	3.625	5.375
Accuracy (6)	*3.625*	3.375	3.625	3.625	3.625	3.625	3.5	3.375	2.75	3.625	3.375	3.5	3.5	3.625	4	3.625	3.5	6	3.5	3.5	3.5	3.375	4.25	3.625	3.75	4	3.5	3.5
Accuracy (7)	*71*	71.125	69.875	71.25	71.125	71.125	65	71.125	71.125	71.5	64.75	71.125	70.5	70.125	69.75	71.125	71	70.875	71.125	69.75	59.125	64.375	70.25	72.5	71.625	71.125	71	71.125
Accuracy (8)	*41.125*	40.375	40.125	41.25	41.25	41.25	41.125	40.375	41.125	40	41.25	40	41.625	41.625	38.25	41.125	40.25	39	41.25	41.25	41	41.25	41.125	41.25	41.5	41.125	41.125	41.125
Accuracy (9)	*42*	42	42	43.125	42	42.125	42	42	42	42	42	42.125	42.125	41.75	28.25	42	42	42	42	40.5	42	42	40.75	42	41.875	38.125	42	39.625
Accuracy (10)	*10.25*	9.375	8.5	10.25	9.625	9.5	9.625	9.375	8.75	9.5	9	9.625	9.625	9.75	9.5	9.5	9.5	12	9.625	9	9.75	9.25	9	9.625	9.625	12.5	9.125	9.5