AN ANALYSIS OF EXPERIMENTAL DATA TO DETERMINE THE VALIDITY OF ASPECTS OF TOLERANCE REQUIREMENT GENERAL THEORY

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The paper examines the data resulting from the first of two experiments designed to examine aspects of tolerance requirement general theory as proposed by the author. The experiments were designed as an initial study into a possible relationship between task difficulty and time taken to carry out the task. Previous papers have examined the process of designing experiments suitable for the intended purpose. This paper concentrates on the analysis of the data resulting from one of these experiments. The analysis seeks to identify and eliminate any possible spurious relationships which may be suggested by the data, with the objective being to establish, if possible, the form of a robust and repeatable mathematical relationship between one aspect of the production process and time taken. The aspect focused on is that of tolerance requirements, which are not seen in the context of this research as being optimum plus-or-minus values for tolerance sizes. Tolerance requirement general theory considers there to be zero allowance for deviation from intended position. Data analysis results in a re-examination of the proposed nature of tolerance requirements, and further development of tolerance requirement general theory.

Keywords: Task difficulty, tolerance requirement general theory.

INVESTIGATION OF 'TOLERANCE REQUIREMENTS' GENERAL THEORY

Tolerance requirements have been suggested as being an important attribute within the concept of buildability assessment proposed by the author [Moore (1997a)]. Emphasis is therefore placed upon investigating the relevance of the tolerance requirements attribute to the functionality of the proposed prototype automated design aid (ADA). The background to the ADA proposals has been covered elsewhere [Moore (1996: 29 - 46)]. The design of the experiments used within this phase of the author's research, and the resource constraints upon their operation, have been discussed previously [Moore (1997b)] and will not be covered again here. This paper focuses on the results from the panel 'A' component of the first experiment carried out, which utilised two differing brickwork panel designs (Fig. 1). A further important consideration is that this research does not concern itself solely and immediately with the productivity of the construction method. Rather it seeks to determine a basis for such a future examination by studying:

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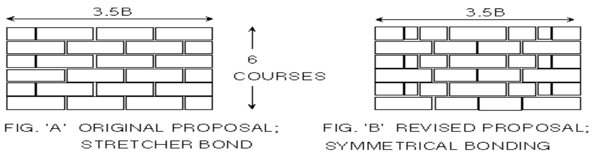

Figure 1. Brickwork panels as used in experiment no. 1 [Moore, Tunnicliffe (1994)].

i) if any objective relationship between the demands of the 'as drawn' design and the response of the construction process, at the task level, can be identified.

ii) the basis and nature of such a relationship.

A final consideration regards the volunteers used in the experiment. Students, rather than fully skilled bricklayers were used. Experienced bricklayers were not seen as being required at this stage of the research, due to the emphasis placed on manual tracking research in the development of the investigative experiment. It was decided that students of varying expertise, ranging from novice to near-expert, would more clearly demonstrate how the development of expertise (skill) affected manual tracking abilities. The use of student bricklayers was not seen as being a significant problem.

TOLERANCE REQUIREMENTS: EXPERIMENT NO. 1

All models used within this experimental work were developed in consultation with brickwork staff at Southfields College (Leicester) so as to enable testing of the presumed relationship between task difficulty and time taken without the introduction of new knowledge to the participating students. All models used are similar to existing models used within the NVQ assessment framework. However, it is worth noting that construction work is invariably prototype in nature, and therefore any task will represent, at some level, the opportunity to further develop expertise. Given the intention within this research to identify any characteristics of construction work which could form the basis of a generic assessment tool for buildability at the task level, such opportunities to develop further individual expertise are suggested as not being problematic. This is particularly so given the controlled nature of the experiments.

The experiment results for panel 'A' are presented in Table 1, and indicate varying work performance rates on each course of the panel. Given that the tolerance requirements are effectively the same on each course of panel 'A', general TR theory would predict that each course would take a similar amount of time to complete. The result being a small, or even zero, variation in the time taken for each of courses 2-6 over that taken for course 1. Examination of column three in Table 1 shows that this is not the case. The smallest variation is +7.84%, whilst the largest is +63.32%: both values being achieved by the same student. The original perception of tolerance requirements may have been in error, with some variation in tolerance requirements taking place, causing production times to vary over each course.

The suggestion (by the author) that bricklaying be regarded as a manual tracking task offers a possible explanation for the disparity in panel 'A' results. Within a manual tracking task there are standards which the participant is trying to achieve. Brickwork standards are in the form of a relationship between a given brick and other bricks in the same course, and also the preceding course(s), if any. Such standards have long been implied, if not explicitly stated, within the rules governing the achievement of satisfactory brickwork [Adams (1913), and see also Figure 2].

PANEL 'A' STUDENT 1.	TIME PER COURSE (1-6) IN STD. MINS.	VARIATION % (+/-) OVER 1st COURSE	TIMES LEVEL USED	VARIATION % (+/-) IN LEVEL USE OVER 1st COURSE
Course 1	3.19		5	
2	3.44	+7.84	8	+60.00
3	4.89	+53.29	8	+60.00
4	4.18	+31.03	9	+80.00
5	5.21	+63.32	11	+120.00
6	3.64	+14.11	8	+60.00
TOTALS	24.55	**Range=55.48**	49	**Range=60.00**
STUDENT 2.				
Course 1	1.80		3	
2	2.16	+20.00	6	+100
3	2.80	+55.55	8	+167
4	2.34	+30.00	6	+100
5	2.61	+45.00	8	+167
6	2.54	+41.11	8	+167
TOTALS	14.25	**Range=35.55**	*39*	***Range=67.00***

Table 1. Experiment No. 1:Panel 'A', Results.[Moore (1997a)]

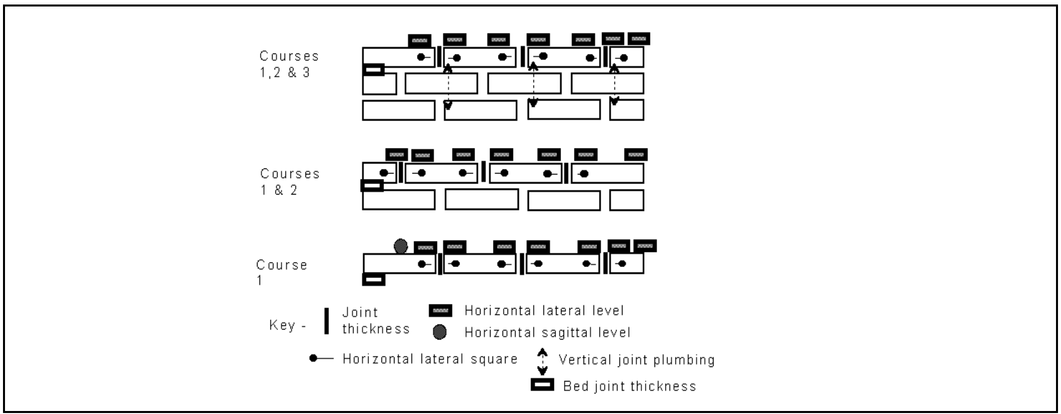

Figure 2. Examples of suggested Tolerance Requirements: panel 'A'. [Moore (1997a)]

To achieve these tracking standards, monitoring of the brickwork has to be carried out as the work proceeds, thereby slowing the work rate if the student does not have sufficient expertise to carry out monitoring and placing as part of one process. Unproductive time is therefore being created when the student interrupts the laying of bricks to explicitly monitor the completed work's standards. A component of the recorded student times will be unproductive time utilised for the explicit monitoring of tolerance requirements, and no other behaviour which could be classed as productive. Examination of the video recording for experiment 1 produced data on explicit monitoring time, relevant to each course, for both students, which was subtracted from the original data, to give values for productive (as opposed to production) time. The resultant times, and revised variation values, illustrate the effect of explicit monitoring on time taken to complete each course. By extracting explicit monitoring time from the overall production time, the resultant revised productive time per course can be examined. As one example, the revised panel 'A' productive times on courses 2-6 for student 2 vary, in comparison to course 1, to a reduced extent (compared to Table 1 results) across a range of 28.36%; a reduction of 22.22% in variation on the unadjusted total times per course. By dealing with productive time and monitoring time separately, the range of variation which the prototype ADA will have to deal with is beneficially reduced. However, the author attempted a number of approaches to reduce further the distortion within the data. These approaches focused on discerning the role of monitoring within the production process.

Prior to making any attempts at reduction of distortion within the results, they were used to produce a forecast of monitoring and productive times. These times were for a student (student 3) of a higher level of expertise (>2 years but <3 years of experience; approaching NVQ Level 3) in completing panel 'A'. In this manner a basic evaluation of the premise that increasing expertise levels and reducing work times exist in a 'lock-step' relationship can be carried out. By forecasting monitoring and productive times for student 3 on the basis of the incremental change in performance from student 1 to student 2, a broad feel for the relationship between expertise and production may be obtained. A detailed discussion of the work carried out by student 3 will be presented in a future paper, dealing with experiment 2. However, at this point there is a value in comparing the actual times achieved by student 3 to the times forecast by the basic model of performance. The basic model is not good at forecasting monitoring times in general: an error range of 103.59%, with a maximum error of -

65.28%. It does, however, achieve low levels of error on courses 1 and 6. The situation regarding productive time forecasting is better: an error range of 49.40%, and a maximum error of -63.69%. The significance of these error ranges should be considered in terms of points forming the focus for the distortion reduction exercise:

1. their relevance to the 'lock-step' premise discussed previously. It is suggested that error ranges of the magnitude calculated indicate a relationship between expertise (in perception of task difficulty) and production times of greater complexity than that contained within the above premise.
2. the total error ranges deemed acceptable by other forecasting techniques. For method time measurement (MTM) techniques, for example, acceptable levels of analysis accuracy are at best + or - 20%, giving a total error range of 40% [Konz (1995)]. Total error for student 3 forecast monitoring time is 111.95%, and total error range for forecast productive time is 63.69%.

It is important to reiterate at this point that this research intends only to test the feasibility of a prototype ADA which attempts to model, rather than precisely replicate, those skills relevant to particular operative high level tasks. There will therefore be no significant weakness in developing the prototype on the basis of formulaic representations which closely represent, rather than precisely replicate, operative skill. This research seeks only to develop a formulaic representation closely approximating to operative skill in *responding to varying tolerance requirements* within the high level task of bricklaying. The key consideration is suggested as being the student's <u>perception</u> of difficulty in relation to varying TR values.

PANEL 'A' DISTORTION REDUCTION: METHOD 1

This focused on reducing distortion within the monitoring times. The starting point being a consideration of what represents an ideal figure for the use of the bricklayer's level: use of a level beyond this figure would represent a squandering of possible productive time, whilst use below this figure would represent a possible reduction in product quality. Consideration by the author of the tracking requirements discussed previously, combined with an evaluation of how plumb, level and square may be best achieved with minimum use of the level, resulted in the following values: course 1, four instances of level use; course 2, six instances; courses 3 - 6 inclusive, eight instances. Monitoring times for each course were adjusted on the basis of average time per instance of level use for students 1 and 2, which was added or subtracted as required from the actual monitoring times achieved.

Adjusted monitoring times occupied an error range (and total error) of 96.35%: a 6.81% decrease over the unadjusted times, indicating that adjusting monitoring times for students 1 and 2 only was not significantly beneficial with regard to reducing distortion in the experiment results. The adjusted monitoring time values for students 1, 2 and 3 were then subjected to regression analysis to determine their predictive value, which was determined at an R-sq adjusted value of 99.3% for the regression equation of: *Student 3 Monitoring Time = 0.178 + 0.302(Student 1 adjusted monitoring time) + 0.20(Student 2 adjusted monitoring time).* There are, however, two problems concerning this regression equation:

1. This equation can forecast adjusted monitoring time only on the basis of previously recorded monitoring times which have been adjusted for the number of times the level should be used per course.

2. Adjustment of the above type is imposing an ideal method upon one aspect of the construction process.

The explicit monitoring time component can only be of value in the assessment of buildability if an ideal manner of explicit monitoring, rather than a variable actual manner, can be accepted. Within the context of comparing two versions of a given design, the use of such an ideal is suggested as not being unduly problematic.

PANEL 'A' DISTORTION REDUCTION: METHOD 2

Method 2 considered distortion within the recorded productive times. Because explicit monitoring within the experiment was recorded separately from productive time, no distortion within the overall production time could be attributed to varying usage of the level. Other factors which were determined by the author as not having any definable relationship to distortion with respect to production times on panel 'A' were: brick cutting, with the number and size of cut bricks being consistent throughout all courses of panel 'A'; pointing of joints, with no pointing being required.

An aspect of tolerance requirements not covered by explicit monitoring, for which the term *tacit monitoring* is proposed by the author, was then considered. Tacit monitoring, as recognised by this research, does not present itself as an interruption of the production process and is therefore not explicitly measured. Whilst the precise nature of any interaction between tacit monitoring and rate of production can only be determined with the analysis of further data, it is possible to consider the general nature of such an interaction within the context of the accuracy component of an operative's skill. Tacit monitoring is suggested (by the author) as being a possible generic task existing within the umbrella manual tracking. Within this context, tacit monitoring can be argued to involve monitoring the work in progress against work completed, and a projection (mental model) by the operative of work to be done, in terms of x,y,z co-ordinate data, hence the proposed relationship with the accuracy component of skill. Suggested total tolerance requirements per course in panel 'A', are illustrated in Figure 3.

Course.	**Relevant Tolerance Requirements and number of occurrences eg. (2)**	**Total Requirements**
No. 1	Horizontal lateral level [HLL] (4), Horizontal sagittal level [HSL] (8), Vertical joint thickness [VJT] (3), Horizontal joint thickness [HJT] (1), Horizontal lateral square [HLS] (8), Sagittal plumb [SP] (2)	26
No. 2	As course 1 (26) plus: SP (2), HLS (2)	30
No. 3	As course 2 (3) plus: Vertical joint plumb [VJP] (4)	34
No. 4+	As course 3, plus: Lateral ranging [LR] (2)	36

Figure 3. Total tolerance requirements per course: panel 'A'. [Moore (1997a)]

Within the context of this research, 'tolerance requirements' does not involve any consideration of acceptable tolerances normally encountered within the construction process. In effect, there are zero tolerances within 'tolerance requirements': the operative is assumed to be striving for zero defects. The proposed ADA therefore builds up its own 'mental map' of the artefact to be produced based on zero tolerances. Given the scale of design detail typically produced at sketch design stage (1:100) there appears to be no logical argument for considering acceptable levels of error (tolerances), which may be at the level of ± 1mm, within the proposed design aid.

The initial stage of testing the data regarding student productive time and total tolerance requirements per course was to carry out a regression analysis. Evidence of a strong relationship between the factors would indicate a means of assessing task difficulty on an objective basis; tolerance requirements. Regression analysis produced an equation of the relationship between the two factors of:

Student 2 Productive Time = -0.308 - 0.0237(Student 1 Pt) + 0.0157(TR).
… **(-1.32) (-0.39) (5.92)**
R^2 = 62.9%; R^2 = 59.3%; DW = 1.92.

This model was reasonably accurate regarding a statistically significant link between tolerance requirements and student 2 productive times (t _ 1.717). There is also no evidence of autocorrelation (DW _ 1.45). There is, however no statistically significant connection between student 2 placing time and the constant. In order to improve upon this accuracy, the author examined ways in which the tacit monitoring element could be extracted from productive time data, and assessed in terms of time (standard minutes). The reasoning behind this approach was that if increasing tolerance requirements do slow down the rate of production, the most obvious source of that slow down would be increased levels of tacit, rather than explicit, monitoring. This required searching the literature domain of cognitive psychology, with particular reference to information processing by operatives carrying out manual tracking tasks.

Information processing research suggests that in manual tracking tasks a key consideration is the need for the operative's eyes to be looking directly at the target, or object, so that the brain can acquire the required detail about it [Poulton (1974)]. This is particularly important regarding the role of stepped tracking in the development of expertise in manual tasks such as bricklaying. Differing levels of student performance are suggested as possibly being an example of the relationship between expertise and stepped tracking. Stepped tracking occurs when an operative chooses to make large movements at high speed prior to slowing as the target is approached. This behaviour results from the operative learning through experience that tracking at a constant speed between start and finish points of a movement results in high levels of placing inaccuracy, or acquiring of the target, resulting in repetitive corrective action. This is especially so when the target is small, as illustrated by Craik's ratio rule and Fitt's ratio rule [Poulton (1974)]. Both indicate that large quick movements have an error, roughly proportional to their size, at an average of 5%. An error of 5% within a movement covering a distance of 600mm would result in a placement error of approximately 30mm. Given that brickwork joint sizes are typically 10mm in width, a placement error of 30mm would not be acceptable.

PLACING TIMES AND TOLERANCE REQUIREMENTS

Data for tracking and placing times, along with the tolerance requirements, was tested for the strength of any relationships between the three factors through a stepwise regression. Tolerance requirements and the placing times for student 2 demonstrated the strongest relationship with a t-ratio value of 11.04 (a ratio of ≥1.717 indicates a statistically significant relationship at a 95% level of confidence). Prior to examining this relationship specifically, the data for placing times and tolerance requirements for each student was placed through a regression analysis to provide a base equation and R-sq.adjusted value for evaluation of subsequent equations. The resultant equations and analysis data were: …

1. Student 1 Pt = 0.147 + 0.0040(TR). R^2 = 3.1%; R^2 = 0.0%;
   (1.49) (0.84) DW = 2.08.

…

2. Student 2 Pt = -0.0449 + 0.0167(TR). R^2 = 78.1%; R^2 = 77.1%;
   (-3.21) (8.87) DW = 2.01.

There is no statistically significant relationship between student 1 placing times and tolerance requirements, and there is no evidence of autocorrelation (DW statistic of 1.45 to 4 indicates no autocorrelation, although a value of 2 is generally seen as ideal). Student 2 data, however, exhibits a statistically significant relationship between the two variables, with no evidence of autocorrelation.

STEP No.	**ACTIONS REQUIRED (Artifact 1: panel 'A')**
1.	Take wall thickness, 'z', ÷ by brick length (mm), classify wall as brick multiple: 102.5÷215 = 0.5 brick wall. Record.
2.	Take wall length, 'x', ÷ by brick length, record number of bricks (3.65), subtract whole bricks from total (3.65 - 3 = 0.65), convert part brick to mm (139), subtract number of whole bricks x 10mm (3x10 = 30) from part brick (139 - 30 = 109), classify to nearest multiple of brick (0.5b), sum whole and multiple for total per course = 3.5b
3.	Record number of vertical joints; total bricks / course - 1, or multiple (3.65 -0.65 = 3)
4.	Take wall height, 'y', ÷ by brick height (65mm), record no. of courses (6.9), subtract whole bricks from total (6.9 - 6 = 0.9), convert part brick to mm (58.5), subtract no. of whole bricks x 10mm (60) for number of bed joints, classify remainder to nearest multiple of brick (0), record no. of courses (6)
5.	Record total number of bricks in wall (21)
6.	Take course 1, go to brick 1, define tolerance requirements (TR) as: 'x' axis, (0); 'y' axis, 1 (HLL-see Fig. 60), 1 (BJT), 1+1 (HSL); 'z' axis, 1+1 (HLS), 1 (SP) sum TR for brick 1 = 7. Go to brick 2, take brick 1 value, subtract 1 (BJT), subtract 1 (SP), add 1 (VJT), sum TR for brick 2 = 6. Repeat until last brick, take brick 2 value, add 1 (SP), sum TR for brick = 7. Sum TR for course = 26.
7.	Take course 2, go to brick 1, define TR as: course 1, brick 1, add 1(SP); sum TR for brick 1 = 8. Go to brick 2, take brick 1 TR value, subtract 1 (SP), subtract 1 (BJT), add 1 (LP), sum TR for brick 2 = 7. Repeat until end of bricks on course 2. For final brick add 1(SP), sum TR for course = 30
8.	Take course 3, repeat TR actions per brick as course 1, add 1 per brick (VJP), Sum TR for course = 34
9.	Take course 4, repeat defining actions per brick as course 3, take brick 1, add 1 (lateral ranging), take end brick, add 1 (lateral ranging), sum TR for course = 36.
10.	Repeat until all courses assessed
11.	Tabulate TR values / brick / course

Figure 4. Tolerance requirement calculation algorithm (Version 1).

The resultant equation suggests that students within this group see tolerance requirements (either explicitly or implicitly) as accounting for approximately 77% of the possible causes of task difficulty. Thus student 2 equation was accepted as a suitable basis upon which to develop the general theory of tolerance requirements. Varying approaches to identifying and counting tolerance requirements (TR) were attempted. Each approach was constrained by the requirement that TR must be definable in terms of x,y,z co-ordinates, in order that they can be located within a CAD workspace. A minimum count of three TR per brick was achieved using one approach, and a maximum of eleven per brick using a different approach. This variation resulted in a best R-sq.adj. value of 77.1% and a worst value of 43.9%. Small differences in the tolerance requirement count for individual bricks had a significant effect on the resultant R-sq. value. To ensure consistency, the author produced a TR calculation algorithm, based on the logic for TR illustrated previously.

The TR count resulting from the algorithm was then used in conjunction with the equation: Student 2 Pt = -0.0449 + 0.0167(TR) in order to produce a forecast placing time for each brick. An iterative process followed, in which the forecast time was checked against the actual time and the difference calculated as a percentage error, and the TR algorithm was then honed until an acceptable level of error was achieved. The algorithm which achieved the lowest error is presented in Figure four. This algorithm is proposed as the basis of further developing the accuracy component of skill modelling within the prototype ADA by predicting placing times for panel design 'B'.

CONCLUSIONS

The experimental work has indicated the existence of a number of components within productive times for the high level task of bricklaying. Possibly the most important of these is tacit monitoring, in as much as a relationship appears to exist between the extent of tacit monitoring per brick and the tolerance requirement count for that brick. This relationship will be evaluated further in future experimental work.

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