

Cognitive task analysis for Virtual Reality Training: 
the case of CNC tool offsetting

Dimitris NATHANAEL  George-Christopher VOSNIAKOS  Stergios MOSIALOS

National Technical University of Athens, School of Mechanical Engineering
GR-15780, Zografou, GREECE
dnathan@central.ntua.gr vosniak@central.ntua.gr steргiosmosialos@yahoo.gr

ABSTRACT

Motivation – To examine if cognitive task analysis of expert machinists can be effective in developing a virtual reality based training system for CNC tool offsetting.

Research approach – A cognitive task analysis of expert machinists was conducted which informed the development of a VR training system for CNC tool offsetting. Subsequently the effectiveness of the analysis was evaluated by conducting an experiment with 31 mechanical engineering students.

Findings/Design – The virtual reality system demonstrated positive training transfer for the task of tool offsetting. The above indicates that the cognitive task analysis performed was effective in identifying a number of key skills of the tool offsetting task.

Research limitations/Implications – The study does not prove the superiority of cognitive task analysis over other approaches for specifying virtual reality training systems, since it does not compare the cognitively tuned system with another one.

Originality/Value – The present work provides evidence that skill transfer can be achieved even with low physical fidelity provided that the cognitive organization of a task is adequately mapped in the virtual reality system.

Take away message – Further and beyond fidelity issues, cognitive task analysis can provide important input in specifying effective VR training systems.

Keywords
Virtual Reality, Simulation, Training, CNC machining, sensory – motor skills.

INTRODUCTION

Virtual reality systems are being used for training with considerable success in many work domains. Actually in any training situation, where either the cost or the possible negative consequences of exposing trainees to the real task environment are considerable, Virtual Reality based Training Systems (VRTS) may provide a valuable alternative. That being so, there are still many unsolved questions as of the effectiveness of VRTS for skill transfer. For example, a frequent criticism is that they are not effective for tasks that are characterized by a significant perceptual and/or motor component. This is partly due to the fact that most systems do not have the necessary physical fidelity to mimic the resolution of the physical world. However, one should not forget that some of the most successful VRTS for motor skill training such as the MIST VR surgical simulator (Gallagher et al. 1999) have been highly successful even though they are judged as of very low fidelity by today’s standards. Technical refinements will always be welcome but they cannot guarantee successful training as such. The success of MIST MR in particular was partly due to a preliminary ergonomics analysis of Laparoscopic surgery at the design stage (Gallagher et all 1998). In fact, human factors input or lack off, in the development of Virtual Reality systems has been a common argument for success or failure of such systems (Wilson et al. 2005, Stedmon and Stone 2001). Few studies have tackled the issue from a cognitive ergonomics point of view. Dankelman et al (2003) and Wentink et al (2003), in a surgical context, have used Jens Rassmussen’s classification of human behaviour at the skill – rule – knowledge levels to discuss the effectiveness of Virtual Reality systems. In the CNC domain, Lin et al. (2002) used goal decomposition i.e. a variation of hierarchical task analysis to represent task execution scenarios and associated training objectives. The present paper reports on a cognitive task analysis following the ecological approach (Flach 2000). It attempts to reveal the phenomenology of the CNC tool offsetting activity and to use it as a basis for the specification of a VRTS. The specific application demonstrates how cognitive task analysis during VRTS development may provide valuable insights and lead to successful skill transfer even for tasks with significant perceptual and/or motor component.

THE APPLICATION DOMAIN

Machining is a domain where virtual reality is increasingly used for training purposes. In machining operations VRTS can provide trainees with a high degree of freedom for operation compared to actual Computed Numerically Controlled Machining Centers (CNC MCs). This is because the results of improper operation can be simulated without incurring the associated costs in terms of human injuries or
A typical task requiring particular training in perceptual skills is Tool Length Offsetting (TLO) on MCs. Cutting tool length offsetting is a prerequisite for subsequent CNC program execution. It involves the determination of the Z coordinate of a MC which physically corresponds to the tool tip. It is considered a critical task for the dimensional accuracy of the machined product and is repeated for every single part to be machined. TLO can also be performed through laser sensors, but due to their cost and to their inadequacy for many industrial environments, the manual method is commonplace in most industrial applications. Manual TLO is performed with the operator slowly closing-in the rotating milling cutter until he “judges or feels” that the cutter has just touched (or is about to touch) the workpiece surface. The milling cutter is controlled by means of a rotary knob on the machine console with 3 to 4 speed scales. TLO is considered a delicate and potentially hazardous operation since depending on the lowering speed the workpiece may be damaged or the cutter may break.

THE VIRTUAL REALITY TRAINING SYSTEM

A VR model of a typical three axis vertical spindle machining centre (HAAS™) was developed using SOLIDWORKSTM for 3D part design and VIRTOOLS™ for part assembly and simulation. The control panel was a custom-made physical model of the real HAAS control panel. The simulation environment can run in a typical PC with screen or video projection without any particular immersive interface. The VRTS incorporates a three dimensional representation of the cutting area of the CNC, spindle and tool movement and rotation, workpiece penetration etc. Other essential features incorporated in the VRTS are i) variable viewing angle of the machine workspace (by means of head sensor or mouse) ii) machine and cutting sound based on sprinkle speed and workpiece penetration and iii) multiple source virtual lighting with shadows (Figure 1).

The physical model of the control console is a semi-functional copy of the real HAAS machine with fully operational rotary knob control, speed scale selection push buttons and numerical display. A physical model was chosen for the control console because it provides superior feel of manual control and better correspondence with the real machine over a virtual one. The downside of this choice is the VRTS dependence on specific custom-made hardware.

Figure 1: Detail of the VR model

Interface wise, the rotary knob on the VRTS console was designed so as to present tactile resistance close to the real one. Virtual cutting sound and virtual cutting visual effects were developed and implemented to appear at the calculated zero level. Fidelity for the virtual sound was considered acceptable by expert machinists, but visual cues of tool position and cutting were judged as poor at best, due to the immense difference in resolution between reality and the visual simulation.

At a technical level, the dimensional variability (roughness, horizontality etc.) for each virtual workpiece to be worked on was simulated by altering the “true” height of each virtual part through a random number generator. In this way every “trial” of the TLO task had unique zero level, thus preventing cognitive compensation after repeated trials.

THE COGNITIVE TASK ANALYSIS

In training for TLO, it is almost impossible to try to reproduce the necessary subtle stimuli with a useful level of physical fidelity as to make them close to the look and feel of the real thing. The question then becomes “what can actually be transferred as a skill from a VRTS?” In order to determine the skills involved in the TLO task a cognitive task analysis was performed with the participation of four expert machinists.

The analysis was conducted in two phases, a first phase in the real machine for identifying TLO task skills and a second phase in the VRTS for concept validation and fine tuning (see Wilson 1997). The first analysis method consisted of i) observation of task execution along with machinist verbalizations ii) measurements of tools lowering speed and speed scale changes and iii) a posteriori interviews. Each machinist performed the task three times. Task execution strategies were later discussed with each of the four machinists in terms of lowering speed (scale changes and rotary knob clicks) plus visual exploration. Their comments on visual and/or auditory cues were also discussed.

The observations revealed a rather stable pattern in terms of strategy both between consecutive trials and across machinists. Subsequent interviews provided
further insights that clarified observation data. For example, interviews showed that all machinists used a similar mental schema for tool position as a “no see but safe zone” at around 200 μm. However they also revealed that there was divergence across machinists about the most subtle part of the process i.e. the perceptual cues for detecting Zero level. One machinist claimed that he always relies on visual cues, another always on sound while the other two mentioned both. A summary of the results is presented in Table 1.

Table 1: Summary of TLO task analysis results (phase one) based on observations of four machinists.

<table>
<thead>
<tr>
<th>Scale (mm)</th>
<th>Range (μm)</th>
<th>Time (sec)</th>
<th>Cue</th>
<th>Cue type</th>
<th>Typical comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10000 - 2000</td>
<td>5-10</td>
<td>Tool distance from piece</td>
<td>Visual / direct</td>
<td>&quot;See that... The tip is still high up...&quot;</td>
</tr>
<tr>
<td>0.1</td>
<td>200 - 250</td>
<td>10-25</td>
<td>Tool shadow / dim / numerical display</td>
<td>Visual / symbolic</td>
<td>&quot;I know I can still go down safely to around...&quot;</td>
</tr>
<tr>
<td>0.01</td>
<td>20 - 40</td>
<td>20-40</td>
<td>Numerical display</td>
<td>Symbolic</td>
<td>&quot;I want to hear the cutting sound? &quot;you see... it just touched&quot;</td>
</tr>
<tr>
<td>0.001</td>
<td>0 - 10</td>
<td>40-100</td>
<td>Waiting for shine/swarf or cutting sound</td>
<td>Visual / Auditory</td>
<td>&quot;I want to hear the cutting sound?&quot; &quot;you see... it just touched&quot;</td>
</tr>
</tbody>
</table>

The above analysis permitted to identify invariants and salient features at three different levels of abstraction which were incorporated into the virtual task. At a low level, the most critical issue identified was how to specify the appearance and/or fading away of visual / auditory cues. At a medium level the issue was how to specify the induced ambiguity in terms of Zero level, i.e. how vague the relationship between tool coordinates and cues should be. At a high level of abstraction it appeared important to simulate an emergent property of the TLO task, the transition between different phases. These phases were neither dictated from the physical distance between tool and workpiece, nor from perceptual cues alone. They took account of both and corresponded to the transition of the machinists perceptual / representation strategies. In other words the invariants identified were phenomenological in nature rather than purely physical or purely perceptual.

The result was a model of the TLO activity of expert machinists, partly based on the physics, partly on sensory cues and partly on the identified strategy. Specifically the tool offsetting activity was structured in three distinct phases. These were (i) the gross lowering phase, where visual cues are predominant and dependable, (ii) the safe no signal phase where machinists rely on a mental representation of the lowering speed assisted only by the Z coordinates on the digital display and (iii) an unsafe “something waiting to happen” zone, where ears and eyes continuously search for a subtle visual or auditory cue, whichever comes first (Figure 2).

The above model was implemented in the VRTS by simulating the three phases as follows: i) the first phase featured clear visual cues (tool distance from workpiece between 10000 and 2000 μm and diminishing tool shadow between 2000 and 200 μm), ii) the second phase featured no physical cues at all, the tool seemingly touching the part and iii) the third phase introduced a random probability of appearance of auditory or visual signals, around the random Zero level. The slower the lowering speed of the tool, the more subtle the signals were, to the point of threshold sensory discrimination if the lowering steps were at 1 μm scale.

Figure 2: TLO activity cues and invariants along with a schematic representation of tool / workpiece detail

In the second phase of the analysis the four machinists were asked to perform the TLO task in the virtual HAAS machine. Their performance was recorded (see Figure 3) and discussed with them. This method allowed for a progressive calibration of the induced randomness and perceptual cue specification (e.g. intensity curve, signal to noise etc.). The stopping rule of the above process was to reproduce comparable performance as with the real machine.

Figure 3: Graphic representation of TLO performance of four machinists in the virtual machine

EXPERIMENT SET-UP AND RESULTS

In order to evaluate the VRTS effectiveness as an aid for TLO skill development, an experiment was set up with two groups of students (31 in total). These were all fourth year mechanical engineering students with only theoretical training in the functions of CNC MCs. Group A executed five TLO trials directly on the actual CNC while Group B first executed five trials on the VRTS and then another five on the actual MC. All participants were given the same instructions; no time limits for task completion were set. Two quantitative
performance indicators were measured i) achieved accuracy (µm) and ii) time to complete the task (sec).

Table 2: The effect of VR training on TLO performance on the real CNC machine

<table>
<thead>
<tr>
<th></th>
<th>Offsetting Accuracy (µm)</th>
<th>Time to complete (sec)</th>
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<tbody>
<tr>
<td>Group A (not trained)</td>
<td>63.1</td>
<td>134.3</td>
</tr>
<tr>
<td>Group B (VRTS trained)</td>
<td>41.7</td>
<td>78.1</td>
</tr>
</tbody>
</table>

Preliminary analysis of the above indicators showed a marking difference in performance between the two groups. Specifically, group B performance on the actual CNC machine were 37% better in accuracy while at the same time, task execution time was down by 39% (see Table 2) The above results are only indicative as they need further analysis (e.g. statistical significance, learning curve trend, correlation to qualitative data from questionnaires). Nevertheless they do suggest a positive skill transfer from the VRTS to the actual CNC machine.

DISCUSSION

Recent literature suggests that VRTS are very effective for training in procedural tasks. In contrast, for tasks with significant sensory-motor component, use of VRTS does not seem to have a significant effect on real performance (Lin et al. 2002). The work reported in the present paper demonstrates a case where a VRTS was specified and used with success for the training in such a task. It is generally acknowledged that the success of VR for sensory-motor tasks heavily depends on the "physical fidelity" of the virtual machine (Wasfy et al 2005). However for training purposes, perceptual-cognitive validity and relevance, i.e. psychological fidelity (Stone 2008) may be at least as important as physical fidelity. It is suggested that by conducting a preliminary analysis of sensory cues, cognitive representations and competencies of experienced operators in the real task may provide critical design input for effective VR training in tasks with important sensory-motor component. By mapping the invariances of the perceptual – cognitive organization of the task in the VRTS, a system can be designed in a way that directly targets transfer of competence rather than just striving for physical fidelity. The presented work has a demonstrative value. It cannot independently measure the effect of the cognitive task analysis on the success of the VRTS since it influenced its development right from the start. Such an endeavour would require the comparison of the cognitively tuned system with an un-tuned one. Unfortunately, such a comparison has not yet been possible in the course of the present work.

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REFERENCES


