Vibrotactile Feedback in Delicate Virtual Reality Operations

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ABSTRACT
Virtual environments are often unsuitable for delicate operations because of the poverty of feedback, particularly tactile and force feedback. However, force feedback done properly requires large, heavy, expensive equipment. We have experimented with a particular form of tactile feedback using vibration as a substitute for force feedback. Substituting vibration for force feedback is intuitively appealing because it is cheap and low cost. But is it effective? Unfortunately, the answer is both "yes" and "no". We describe an experiment evaluating the effect of vibrotactile sensory substitution on user performance during a grasping task with delicate virtual objects. We found that adding vibrotactile feedback to visual and audio feedback improved task completion time for novice users, but led to increased grasp pressure over repeated uses of the system.

Keywords
User Interface, Virtual Reality, Vibrotactile Feedback

INTRODUCTION
Virtual reality systems immerse their users in an interactive, three-dimensional multimedia environment, presenting computer animation and sound through visual and audio display devices which, typically, encompass the user's entire field of view and hearing (e.g. head-mounted displays and stereo headphones). Some systems also use input devices which track a user's movements and gestures. For example, using a "DataGlove" to direct a computer simulated hand to manipulate computer generated objects (i.e. virtual objects). However, visual and audio feedback in virtual reality systems leaves out one convincing factor in manual manipulation, be it for a game or a surgical simulation: the sense of touch. Specifically, visual and audio feedback do not convey properties such as substance, texture, weight, and pressure as naturally as the sense of touch.

One aspect of touch is the sense of vibration. Easily produced, sensed, and controlled, vibrotactile feedback devices can be used to represent contact forces during manipulations with virtual objects. However, simply noting contact forces is not enough; we also want to know the intensity (or pressure) exerted by the contact. Consider the domains of telemedicine or tele-operation, for example. In these domains an operator not only needs to know when the remotely controlled device contacts something in the remote environment, but also the nature of the contact. For this purpose, the intensity of vibration in the tactile feedback can be mapped to pressure.

The objective of our research is to evaluate and compare the effect of vibrotactile, visual, and audio feedback on user performance in a virtual grasping task. The metrics of this evaluation are the task completion time and the degree of damage, i.e. pressure, inflicted on the grasped object. Completion time is an important measure in time-critical operations, whereas the inflicted pressure reflects the degree of control in a task, which can be vital when fragile objects are being manipulated.

PREVIOUS WORK
There are a number of advantages to using tactile feedback, particularly vibratory feedback ([4], [6], [3], [1]):

- tactile feedback is a non-reactive and passive response (whereas force feedback is reactive and active). Unlike force feedback, it does not induce muscle fatigue, and there is no force which could come into conflict with the user's sense of position.
- tactile feedback devices, especially vibratory feedback directed at the hand, readily exploit the largest, and one of the most sensitive, organs of the body: the skin. Furthermore, the fingertips contain some of the most sensitive sensory receptors, and tactile sensations tend to complement, not burden or conflict with, the visual sensory system.
- most tactile feedback devices, notably vibratory devices, are cheaper, lighter, and easier to assemble than force feedback devices.

The effectiveness of tactile feedback as a sensory substitute for force feedback has already been investigated. For example, Massimino and Sheridan's [4] looked at intensity of vibration substituted for intensity of force. Their experimental apparatus was a master-slave robot manipulator (used to interact with real world objects in another room) coupled

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with a TV monitor (viewing the other room). The master manipulator incorporated a vibrotactile feedback device which varied vibration according to intensity. In addition audio feedback was available, with loudness proportional to force intensity. The results of Massimino and Sheridan's experiments demonstrated that sensory substitution (with audio or tactile feedback) can produce successful results comparable to force feedback in some typical teleoperation tasks[4]. However, the question arises whether enhancing the visual feedback (e.g. using a light, colour schemes, etc.), along with audio would make tactile feedback unnecessary.

A similar study, done by Richard and described by Burdea [1], involved four groups of subjects using the Rutgers Master I (force feedback glove) to manipulate a virtual ball while inflicting a minimum of deformation to it. The first group relied on visual feedback alone. The second relied on additional feedback from the Rutgers Master, simulating the resisting forces of the surface of the ball during a grasp. The third relied on auditory feedback (frequency proportional to ball deformation). The last relied on a LED bar-graph display.

For a hard virtual ball, the feedback from the Rutgers Master I gave the best results, but enhanced visual and audio feedback were significantly better than visual feedback alone. For a soft virtual ball, however, results from audio feedback were significantly superior. The other modes were fairly close together in performance, the best being the force feedback from the Rutgers Master I, followed closely by the visual feedback.

EXPERIMENTAL DESIGN

Our experiment involved a "pick and place" task where the user manipulated delicate objects in a virtual environment.

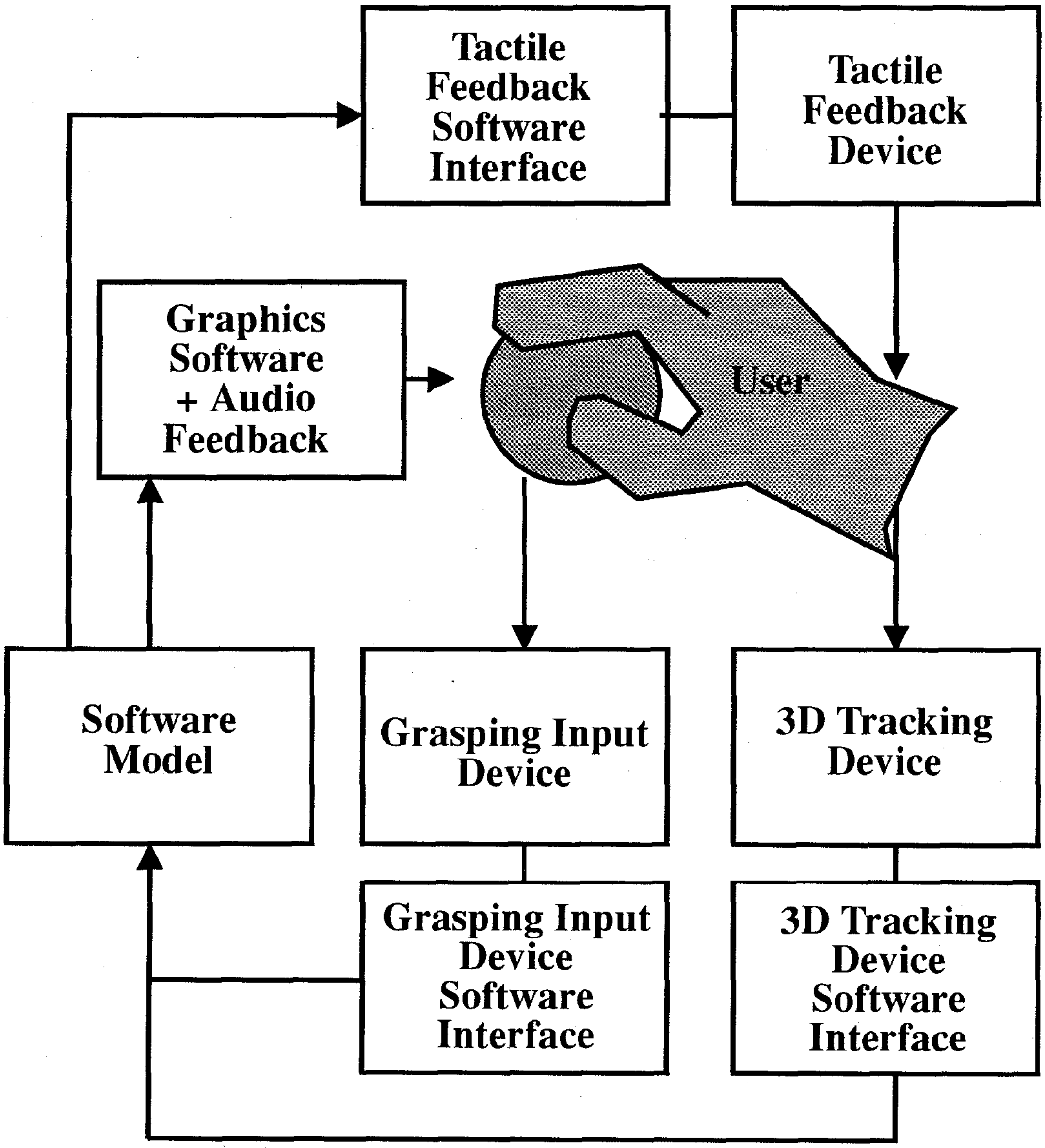


Figure 1: Apparatus Components

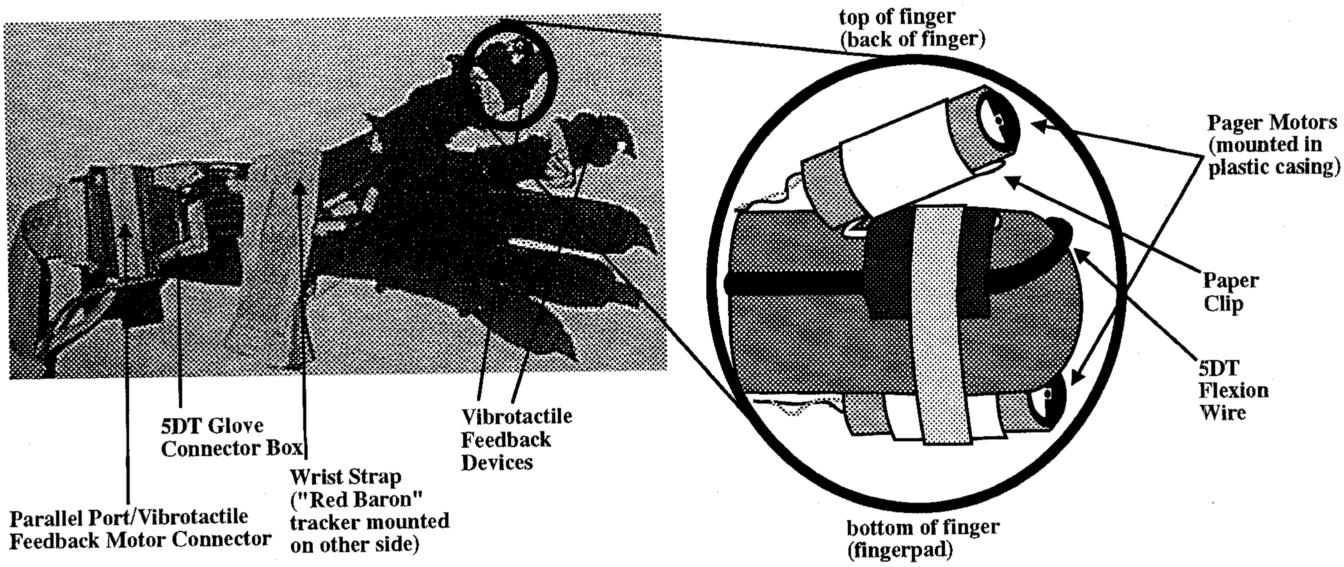


Figure 2: 5DT Glove with Vibrotactile Feedback Devices

The experiment was designed so that there would be no specialized expertise required to perform it. Our experiment simply requires subjects to control a virtual gripper to pick up a (fragile) grape and drop it into a goblet, while circumnavigating any intervening obstacles. Under excessive pressure, the grape explodes, and so the user must grasp using pressures beneath the critical threshold.

Two performance measures were used: task completion time and pressure inflicted on the grasped object.

APPARATUS

The components of the experimental apparatus are shown in Figure 1.

The underlying software presented the virtual environment, which recorded all experimental results and controlled the input and output devices. It was written in C++, using the AVRIL library [5] for graphics and for some of the hardware interfacing. The software ran on a Pentium[1] PC, and graphics output matched or exceeded 30 frames per second at all times.

A 5DT[2] glove was the grasping input device, supplying finger angle information. Attached to the 5DT glove were a "Red Baron" head-tracker,[3] which acted as a 3D tracking device (providing translational information), and a custom built vibrotactile feedback device. Figure 2 shows the 5DT glove and attached devices.

The virtual gripper is modeled as a two-fingered claw, controlled only by the user's thumb and index finger. The grasping task was performed from a fixed viewpoint, showing a side view of the grape, gripper, obstacles, and goblet. The environment was presented on a 17" colour monitor, and all motions were constrained to be on the 2D plane of the monitor, with no accommodation for rotation. These simplifications ensured real-time software performance and gave subjects a unambiguous viewpoint and task to perform. A subject performing the task and a screen shot are shown in Figure 3.

Feedback Modes

The vibrotactile feedback device supplied vibration at an intensity directly proportional to the amount of pressure on a grasped object. In addition, collisions with obstacles induced vibratory feedback proportional to the velocity of impact. Since all motion was constrained in two-dimensions, only four motors were needed for feedback: two for the inner finger and thumb for grasping, and two on the exterior of the finger and thumb for outside collisions (as shown in Figure 2).

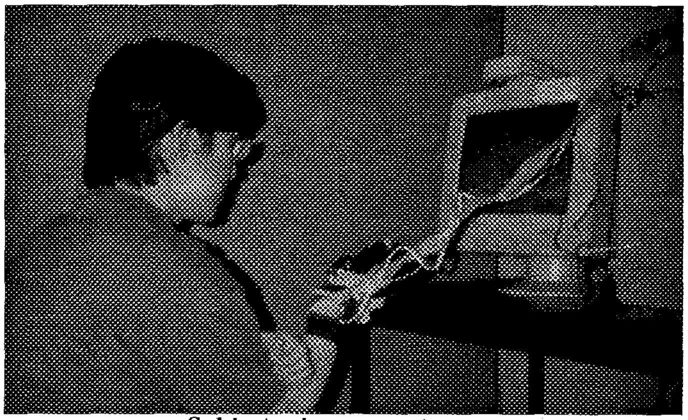
The internal speaker of the computer supplied audio feedback. The grasping pressure or velocity of impact was mapped directly to musical pitch on the C major scale.

Visual feedback was accomplished by using the software to colour the grape during a grasp. The colour scheme is analogous to a traffic light: green for a grasp under 33% of the maximum pressure threshold of the grape, yellow for a grasp between 33% and 66%, and red for above 66%. For each primary colour, the intensity was varied proportionally to pressure (e.g. dark red for very low pressure grasps above 66% and bright red for high pressure grasps near 100%).

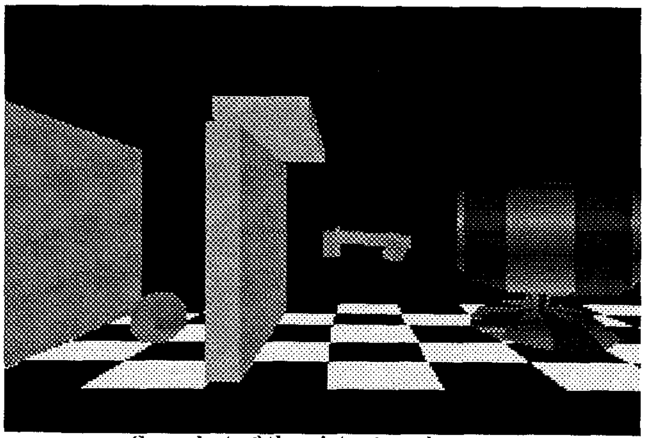
PROCEDURE

24 paid participants (21 male, 3 female between the ages of 16 and 26) were recruited for the experiment. The participants came from undergraduate and graduate programs in Computer Science, Engineering, and Sciences, and were familiar with general computer operations (i.e. word pro-

1. Pentium is a registered trademark of Intel Corp.
2. 5DT is a registered trademark of Fifth Dimension Technologies
3. The "Red Baron" head-tracker is a registered trademark of Logitech Corp.



Subject using apparatus



Snapshot of the virtual environment
(from left to right: grape, gripper, goblet)

Figure 3: Manipulating in the Virtual Environment

cessing, email, etc.). All participants regularly manipulated objects with their right hand, which had to comfortably fit in an average sized glove.

Participants were randomly assigned to one of two equally sized groups of 12: a control group, which performed the pick and place task with visual and audio feedback alone during the entire study, and a tactile feedback group, which performed the pick and place task relying on the same feedback as the control group, plus vibrotactile feedback. Both groups used the same hardware and software apparatus, except that the vibrotactile feedback device was turned off for the control group.

For each participant the experiment consisted of three sessions over one week. The first session commenced with a briefing about the experiment and its objectives. The actual task was demonstrated to the participant. Then a questionnaire was filled out by the participant to determine any relevant perceptual skills (e.g. computer game experience, hand-eye coordination skills) or physical conditions (e.g. vision disorders, hand sensitivity).

The participant was given ten minutes to practice with the apparatus, during which time the investigator provided suggestions on performing the task efficiently. The participant was then asked to repeat the pick-and-place task six times. The gripper trajectories, the pressures exerted on the grape, and the length of time taken to succeed (or fail) were recorded by the computer for every attempt. After all six trials, the session was concluded by the participant filling out an assessment questionnaire to rate his or her overall subjective comfort and performance.

For the second and third sessions, the participant repeated the ten minute practice period, six trials, and assessment questionnaires. While completion time and the extent of grape damage were recorded for each trial, the additional sessions attempted to measure the effect of learning on participant performance.

RESULTS

Statistical analysis was performed using ANOVA tests with repeated measures across the three days of the experiment and any simple effects were tested via a one-way analysis of variance, as described by Howell [2].

	Vibrotactile Feedback		No Vibrotactile Feedback	
	Average	Stdev	Average	Stdev
Day 1	90.28	12.22	95.83	7.54
Day 2	95.83	7.54	94.44	8.21
Day 3	95.83	10.36	94.44	10.36
Overall	93.98	10.66	94.91	8.56

Table 1: Percentage Success in Completing Task

Statistical Analysis

The two metrics for user performance, as described in the introduction of this paper, are completion time and contact pressure. These metrics are described in the following results by two measures:

- Average completion time
- Average pressure

Average completion time is simply the time the subject took to complete the task successfully, averaged over the successful trials in a session (up to six). This reflects the subject's speed in performing the task. The units used are seconds.

Average pressure refers to the average pressure sustained on the grape during a grasp from the initial grasp to the drop into the goblet, averaged over the successful trials in a session (up to six). This reflects the level of pressure control on the grape during a session. The units used are percentages with respect to the breaking threshold of the grape.

Note that all these measures are applied on only the successful trials. Trials where the grape was destroyed (from applying too much pressure) are not counted. However, almost all trials were successful for both vibrotactile and non vibrotactile groups, as indicated in Table 1 (which presents the average and standard deviation of the percentage success over each day). Both groups have comparable success rates on days 2 and 3 and overall. On day 1, the discrepancy is due to a 66% success for two vibrotactile feedback subjects, although on days 2 and 3 these subjects scored 100%. If these anomalous cases are ignored, the vibrotactile group's average success rate on day 1 rises to comparable levels with respect to the control group (similarly, the standard deviation drops to comparable levels), i.e. around 95%

Figure 4 and Figure 5 present the scatter-plots for average completion time and average pressure respectively, for the vibrotactile and control groups. The average result for each day is indicated, as well as error bars representing one standard deviation for each day.

From the previous graphs, it is clear that the majority of the data points lie within a standard deviation of the average. There are a few points that do deviate beyond, suggesting a need to perform outlier removal. Outlier removal was therefore applied to the entire raw data set (i.e. not on the average results, but on every individual successful trial). The resulting plots comparing overall average completion times and average pressures between vibrotactile and control groups over the three sessions, having removed outliers, are presented in the next sections.

Average Completion Time

For average completion time, the ANOVA test indicated an overall significant difference only between the two groups ($F(1,20)=13.26$, $p < 0.05$) and individuals ($F(2,42)=8.97$, $p < 0.05$). The latter result is not surprising since the experiment did not have all subjects use vibrotactile feedback and no vibrotactile feedback. The former result confirms what Figure 6 was suggesting: the vibrotactile feedback group was completing the task faster than the control group.

However, simple effects tests suggest the difference between days 1 and 3 is significant for the control group ($F(2,42)=27.70$, $p < 0.05$). In addition, the difference between the two groups on day 1 is significant ($F(2,f'=55)=30.48$, $p < 0.05$), but by day 3, there appears to be no significant difference. Note that f' refers to an estimate of the degrees of freedom required to account for interaction effects.

The results of the simple effects analysis, when viewed with Figure 6, show that although the vibrotactile feedback group was consistently faster than the control group, by the last day of the experiment, the control group had gained enough experience with the task to nearly match the vibrotactile feedback group's performance.

The flattening out of completion time by day 2 for the control group suggested that the control group achieved maximum familiarity with the task by that day.

Average Pressure

The ANOVA test for average pressure shows a significant difference between the two groups ($F(1,20)=19.02$, $p < 0.05$)) and, again, among individuals ($F(2,42)=5.82$, $p < 0.05$). From Figure 7, the former result suggested that the control group employed less pressure on average during grasping than the vibrotactile feedback group.

The simple effects analysis suggested a significant change between days 1 and 3 for the vibrotactile feedback group ($F(2,42)=12.52$, $p < 0.05$). In addition, the difference between groups is not significant on day 1, but becomes significant on day 3 ($F(2,f'=60)=29.50$, $p < 0.05$).

Referring to Figure 7, the significance results indicate that the vibrotactile feedback group appears to be increasing its average pressure by day 3. The increase is significant not only with respect to the group itself, but is dramatically greater than the control group by day 3 and overall (taking account of all three days of the experiment).

Figure 7 also shows that most users opted to maintain a "yellow" grape (i.e. maintain a grasp within 33%-66% of the maximum pressure threshold).

Results From The Questionnaires

A correlation analysis between age and overall completion time and average pressure gave no significant results. Also no correlation was discovered between previous experience with computer games, virtual reality hardware, and teleoperation/telerobotics equipment. The age and experience correlations were also examined with respect to results on day 1, day 2, and day 3 (instead of overall results), with no significant results. In all of the correlation cases, the correlation r values never exceeded 0.3 and failed significance tests.

The general backgrounds listed by the subjects (e.g. hand-eye coordination skills, vision problems, etc.) were comparable between the two groups, and did not correlate to any exceptional individual cases.

As for the self-assessments, on average, subjects from both groups were in a consensus that they felt there was some

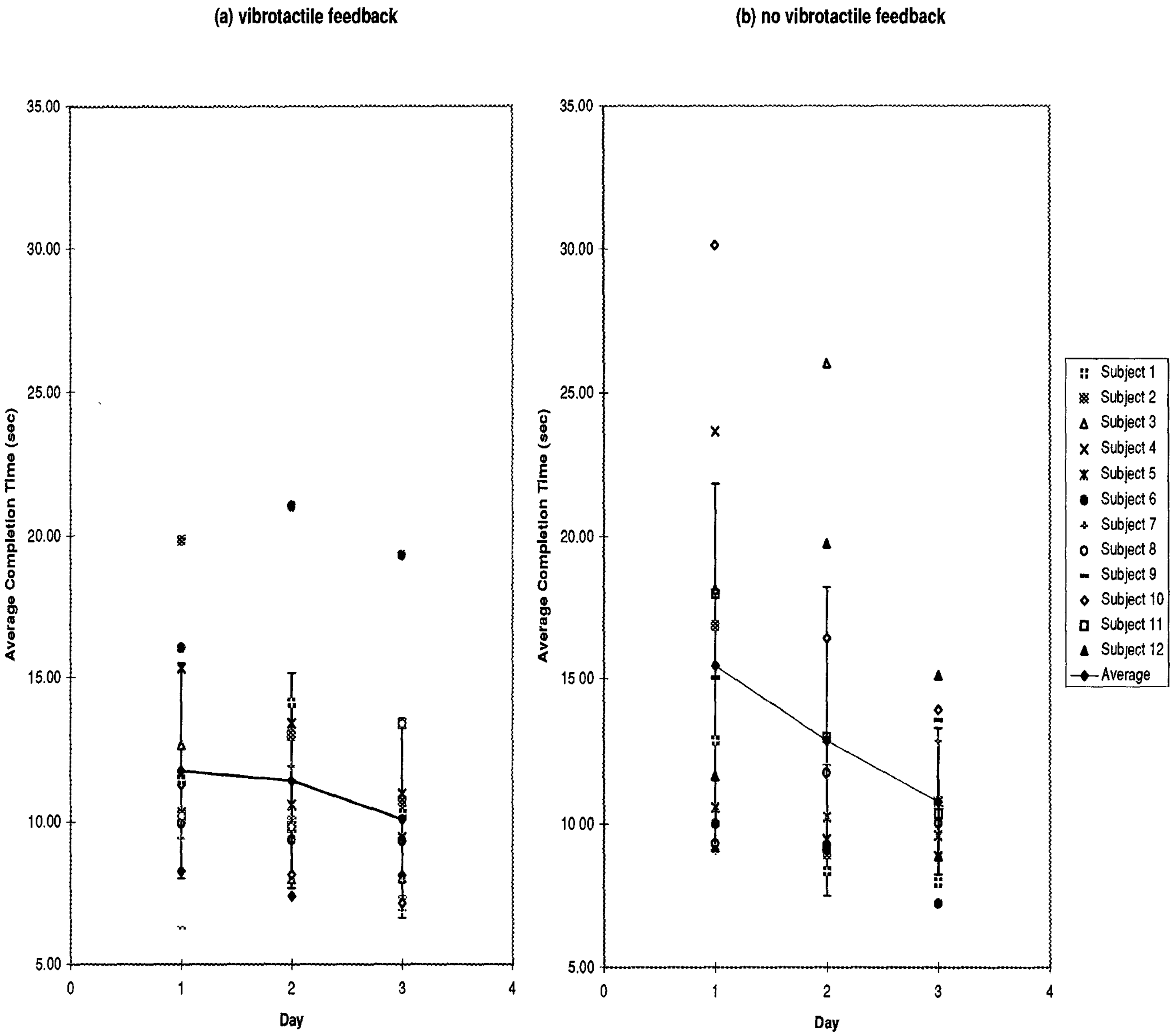


Figure 4: Average Completion Time vs. Days

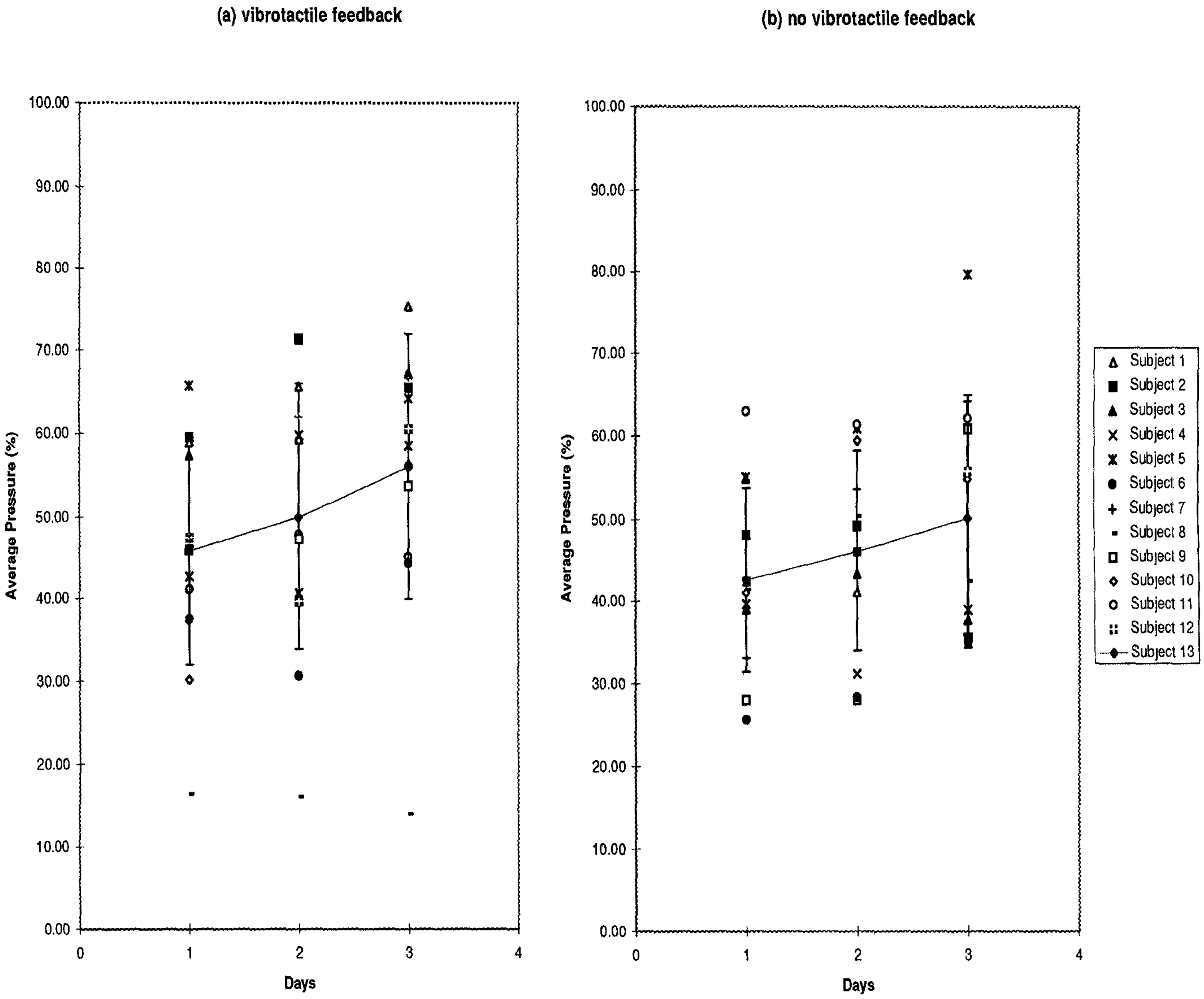


Figure 5: Average Pressure vs. Days

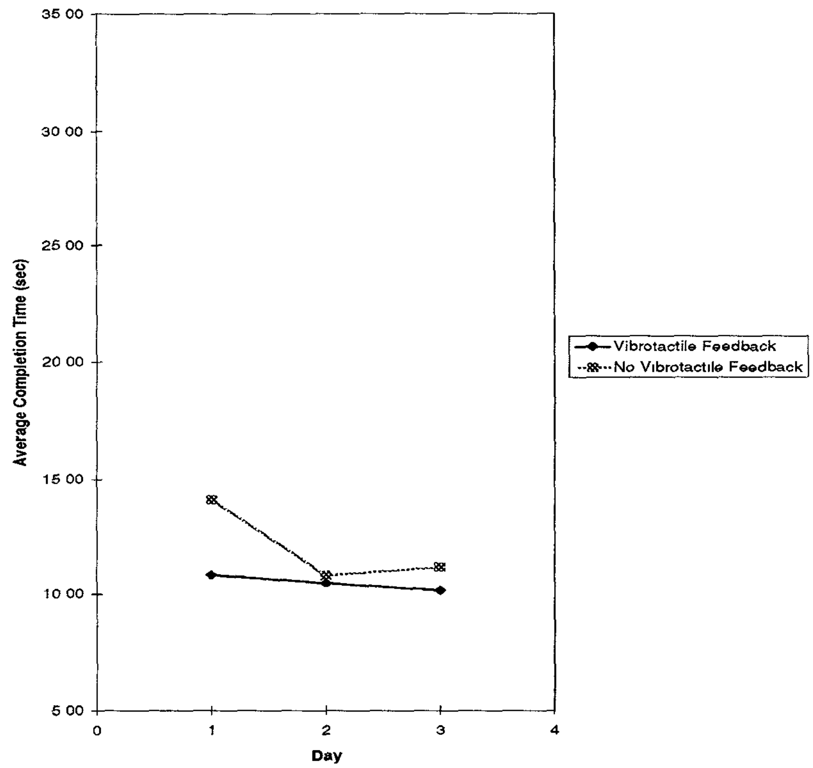


Figure 6: Comparison of Average Completion Times

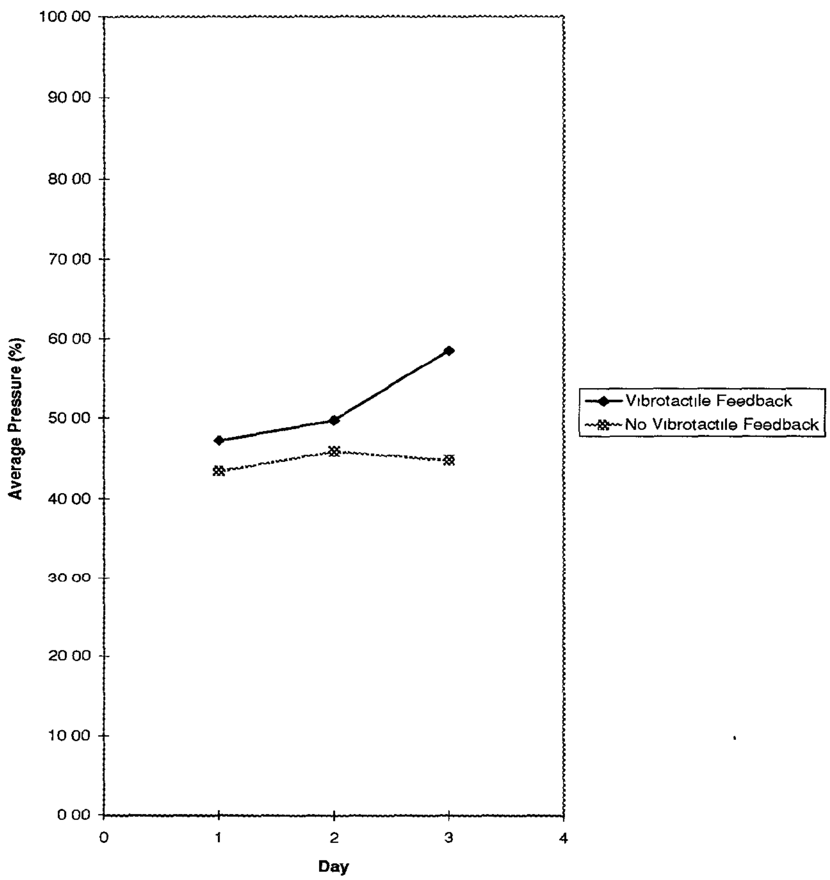


Figure 7: Comparison of Average Pressure

improvement in their performance across the three days, and were comfortable in performing the task.

Almost all subjects in both vibrotactile and non-vibrotactile groups indicated that the grape colour was an important cue. In most cases, the subjects aimed for a "yellow" (medium) grasp, as a light grasp (green) was suspect to slippage, and a heavy grasp (red) was suspect to destruction. On the other hand, opinions varied about audio feedback. Some found it distracting or non-intuitive, whereas others found it to be a useful supplement (interestingly enough, those who found the audio feedback useful tended to have musical backgrounds).

CONCLUSIONS

Two important conclusions can be drawn from the analyses:

- Compared to visual/audio feedback, vibrotactile/visual/audio feedback improves task completion time significantly for first time users.
- Users with vibrotactile/visual/audio feedback inflict *greater* pressure on delicate objects than those with just visual/audio feedback.

The first conclusion matches results from substitution experiments using vibration like that of Massimino and Sheridan [4], but specifically shows that the benefit of vibrotactile feedback is particularly effective on the first day when users are not very experienced. It is, however, important to note with training using informative visual and audio feedback alone, a user can relatively quickly match the performance gained by using vibrotactile feedback.

The second conclusion suggests that the strength in vibrotactile feedback lies in achieving a quick successful grasp (which then leads to faster completion times), and not controlling the degree of pressure on the grasped object. The observed increase in pressure from day 1 to 3, and the fast completion times for the vibrotactile feedback group may be attributed to overconfidence. While the control group also experienced some increase in pressure over the three days, the change was not as statistically significant as for the vibrotactile feedback group. This effect may also indicate overconfidence, but tempered by knowledge that the group did not have vibrotactile feedback.

The general consensus of overall comfort and improvement in performance from user questionnaires is further evidence of this overconfidence. Since the goal of the experiment was to complete the task as quickly as possible, with minimum damage to the grape, the vibrotactile feedback group may have opted for speed over damage, whereas the control group took a more cautious approach. In effect, the addition of better feedback may have enticed the vibrotactile group to become more confident and less cautious, hence causing more damage to the grape.

However, another possibility is that the critical thresholds were too accommodating. As a result, there were insufficient failed trials to focus users on careful pressure control. This is supported by the tendency to maintain a grasp within 33%-66% of the maximum threshold (a "yellow" grape), which was sufficient to keep the grape intact with little risk of catastrophic failure or slippage. If the pressure ranges mapped by "yellow" were offset to lower levels, there may be finer control on the pressure, as subjects commented that there was a strong reliance on visual cues.

In summary, vibrotactile feedback, combined with visual and audio feedback, can be effective for grasping tasks with delicate objects in virtual environments. The chief benefit of including vibrotactile feedback is faster initial training time over visual and audio feedback alone. However, this advantage comes at the cost of increasing pressure inflicted on the grasped object over time.

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BIBLIOGRAPHY

[1] G. Burdea and P. Coiffet. *Virtual Reality Technology*, John Wiley and Sons, Inc., New York, NY, 1994. (updated translation of La Realite Virtuelle).

[2] D.C. Howell. *Statistical Methods for Psychology*. PWS Publishers, Boston, Mass., second edition, 1987.

[3] A. Iggo. *The Senses*. Cambridge University Press, Cambridge, 1982.

[4] M.J. Massimino and T.B. Sheridan. "Sensory substitution for force feedback in teleoperation". *Presence*, 2(4):344-352, Fall 1993.

[5] B. Roehl. *Avril home page and documentation*. URL: http://sunee.uwaterloo.ca/~broehl/avril.html, 1995. (full documentation and sources via ftp://sunee.uwaterloo.ca/pub/avril/avril20.zip).

[6] K.B. Shimoga. "A survey of perceptual feedback issues in dexterous telemanipulation: Part ii. finger touch feedback". In *Proceedings of the IEEE Virtual Reality Annual International Symposium* (VRAIS '93), pages 271-279, Seattle, WA, September 1993.