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Temporal Adaptation and the role of temporal contiguity in spatial behavior

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Temporal Adaptation and the role of temporal contiguity in spatial behavior

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Abstract. Rapid and accurate interaction with the world requires that proper spatial and temporal alignment between sensory modalities be maintained. The introduction of a misalignment (either spatial or temporal) impairs performance on most spatial tasks. For over a century, it has been known that a few minutes of exposure to a spatial misalignment can induce a "recalibration" of intersensory spatial relationships, a phenomenon called Spatial Adaptation. Here, we present evidence that the sensorimotor system can also adapt to intersensory temporal misalignments, a phenomena that we call Temporal Adaptation. Temporal Adaptation is strikingly parallel to Spatial Adaptation, and has strong implications for the understanding of spatial cognition and intersensory integration.

1 General Introduction

When a pebble is tossed into a lake, the water begins to ripple at the instant of contact. This tight coupling of cause and effect holds for most of the universe, and has several important ramifications. Perhaps one of the more important ramifications relates to the relationship between perception and action. When the consequences of our actions are delayed, perceptual feedback about our actions is delayed. Delaying feedback by as little as 45 ms can impair visually guided behavior, while delays of a second or more prohibit the rapid and accurate interaction with the world (Sheridan & Ferrel, 1963; Smith, McCrary, & Smith, 1962; Smith, Wargo, Jones, & Smith, 1963).

Delayed feedback may be thought of as producing an intersensory discrepancy. That is, there is a disagreement between the seen and felt time of occurrence of the action. Such an intersensory discrepancy is formally similar to the intersensory spatial discrepancy studied in prism adaptation (also called Spatial Adaptation). In Spatial Adaptation, special goggles laterally offset the visual field, so that the seen and felt location of an object are different. Since an object can have only one location, the brain takes this mis-alignment as an error, and rapidly recalibrates the intersensory relationship. Prism adaptation has been studied for over 100 years, and a considerable amount has been learned about the underlying mechanisms (for reviews of this work see Bedford, 1993; Welch, 1978).

Despite the formal similarity between the two types of mis-alignments, researchers have found no evidence of any compensation for intersensory temporal discrepancies (e.g. Sheridan & Ferrel, 1963; Smith et al., 1962, 1963). This consistent lack of evidence has lead at least one researcher to suggest that adaptation to intersensory temporal discrepancies is impossible, even in principle (Smith et al., 1962).

For Spatial Adaptation to occur, however, several important conditions must be met. Perhaps the most critical of which is that people must be exposed to the altered sensory relationship. It should be noted, then, that in previous work on temporal mis-alignments, the subjects tended to slow down when exposed to delayed feedback (Sheridan & Ferrel, 1963). It can be readily shown that slowing down essentially negates the effects of the delay. For example, a driver traveling 72 km/h in a car with a 1 second delay must turn the steering wheel 20 meters prior to reaching an intersection. When traveling at 3.6 km/h, however, they need to turn only 1 meter early – they can act as if there were no delay and turn once in the intersection.

Cunningham, Billock, and Tsou (2001) have demonstrated that when people are prevented from slowing down, and thus exposed to the intersensory temporal discrepancy, they do seem to adapt. In that study, the introduction of a 250 ms feedback delay initially impaired performance on an simple obstacle avoidance task, but with a small amount of practice, subjects learned to perform almost equally well with delayed feedback as they could with immediate feedback. Cunningham et al. also provided evidence for two additional hallmarks of adaptation. First, they showed that there was an apparent change in the perceptual relationship between the two modalities. The delayed feedback was easily noticeable at the beginning of training, but by the end of training, the action and its consequences seemed to be temporally simultaneous, despite the 250 ms offset. Second, there was a strong negative aftereffect, one of the primary measures of the strength of adaptation. More specifically, each subject's ability to perform the task without a delay was measured both before and after being exposed to the delay. Learning to perform the task with delayed feedback greatly reduced performance when the delay was removed.

Cunningham et al. used abstract stimuli, a top-down view of the stimuli, and a task with which subjects were unfamiliar. Here, we examine whether temporal adaptation occurs in a more normal situation: Driving in a realistic environment. In addition to allowing one to look at generalization to everyday tasks, driving also allows one to test for another critical hallmark of adaptation: Generalization to novel variations of the task. Specifically, does training on one path improve performance only for that path (a highly specific form of adaptation), or does it generalize to novel paths as well?

2 Experiment 1

2.1 Introduction

In this experiment, we examined whether temporal adaptation can occur for more familiar, everyday tasks. Specifically, we looked to see if humans can learn to drive with delayed feedback, and whether this impairs performance without the delay. This experiment was explicitly designed following the early work on prism adaptation: the task and stimuli were kept constant throughout the experiment (e.g., the same street was used on all trials). Additionally, we ensured that subjects were exposed to the delay, and thus had the chance to adapt to it, by allowing them to control only the direction of travel. The speed was constant for the duration of each trial, with each subject being exposed to several different speeds. Finally, we also examined a larger range of delay magnitudes.

2.2 Methods

2.2.1 Subjects

Twenty-one paid volunteers participated in the experiment. Five subjects developed simulator sickness and did not complete the experiment. Their data have been eliminated from analysis. The data from one additional subject were eliminated as they had never driven before and proved unable to control the car, even at a very slow speed with immediate feedback. Subjects were randomly assigned to one of the three delay magnitude conditions until each condition had a total of 5 subjects.

2.2.2 Apparatus

The virtual road environment was projected onto a half-cylindrical, 180 degree screen (3.15 m high, 7 m in diameter) by a Silicon Graphics Onyx 2 Reality Engine (Figure 1). Subjects controlled the car via a custom-designed, forced feedback steering wheel.

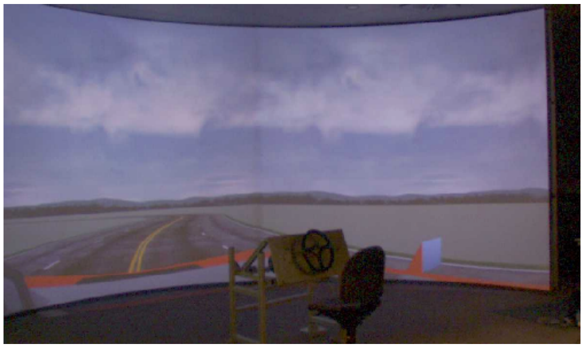

Figure 1: Experimental setup.

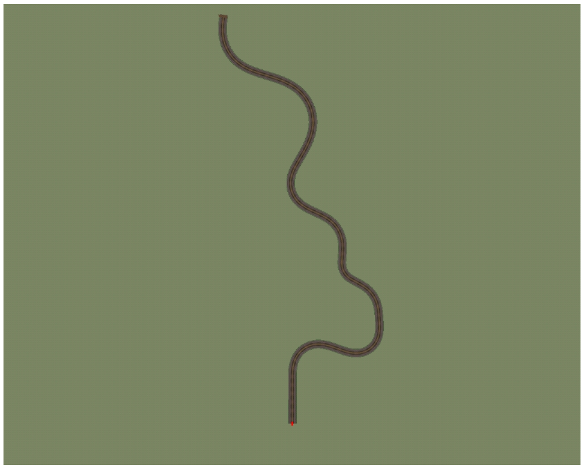

Figure 2: Top down view of the street used in Experiment 1.

2.2.3 Stimuli

To provide a realistic and familiar driving environment, the street (Figure 2) was generated according the formulas that the German government uses in designing real streets (Forschungsgesellschaft für Straßen- und Verkehrswesen: Arbeitsgruppe Straßenentwurf, 1995). Of particular note is that the street was generated using spirals and clothoids, so that the curvature of any given turn increased gradually. Thus, one could drive along the entire street using smooth steering maneuvers. To make the task difficult, the curves were considerably sharper than normal German streets.

2.2.4 Procedure

The subjects maneuvered a virtual car (1.0 m wide by 2.37 m long) along a curved street (10 meters wide) in a high-fidelity virtual environment, using a forced feedback steering wheel. Subjects were asked to drive to the end of the street without ever leaving the road. The street consisted of 4 lanes, and subjects were asked to try and remain in the second lane from the right.

Just as slowing down minimizes the effects of the delay, increasing the speed increases the effects of the delay. To maximize the effects of the delay, very fast speeds were chosen. In general, the speeds were fast enough that subjects were forced to drive at or near the upper limits of their ability. Since driving ability varies considerably across people, a large number of speeds would naturally be desirable. Likewise, the use of many repetitions per speed would increase the resolution of any measurements. Of course, driving along a narrow, curved street at high speeds is a very demanding task, requiring intense concentration from the subjects. The use of a large number of trials, then, would increase the possibility that subjects will become fatigued, to the detriment of their driving performance. To minimize the possibility of fatigue, the number of speeds and repetitions per speed were chosen so that the experiment lasted approximately 30 to 45 minutes.

To familiarize the subjects with the experimental setup in general, and with the control of the virtual car in particular, each subject was given several practice trials (with no feedback delay) prior to the start of the experiment. The experiment consisted of 3 sections (Pre-test, Training, and Post-test):

Pre-test: The Pre-test provides a baseline measurement of how well subjects could drive a virtual car with (nearly) immediate feedback. During the Pre-test, each subject was presented with five repetitions of four speeds ranging from 64 to 108 km/h (18, 22, 26, and 30 m/s) in random order, for a total of 20 trials. The fastest speed at which a subject could successfully drive to the end of the street on at least 4 of the 5 repetitions was recorded as their "Top Speed". This speed played an important role in the Post-test.

Training: During the Training section, the steering wheel controlled the car in the same manner as in the Pre-test, with the sole exception that the effects of steering were delayed. For one third of the subjects, the delay was about 130 ms. For the remaining two thirds, the delay was about 230 or 430 ms, respectively. Prior to the onset of training, subjects were informed that there would be a delay between the steering wheel and the motion of the car.

The order in which the speeds were presented was determined using a shaping-by-approximation training procedure. Specifically, a subject was initially presented with an easy version of the task (i.e., the effects of the delay were minimized by using a slow speed[1]). This slowest speed was repeatedly presented until one of three criterion was met. If a subject successfully reached the end of the street four times in a row (Success Criterion), the speed was increased and training continued. If a subject drove off the street 10 times in a row (Collision Criterion), training ended and the Post-test began. If neither the Success nor the Collision criteria were met within 20 trials (Stalemate Criterion), training ended and the Post-test began.

Post-Test: During the Post-test, performance with immediate feedback was remeasured. At the start of the Post-test, subjects were informed that there would no longer be a delay, and that this section of the experiment was the same as the first section (Pre-test). The difference in performance between the Pre- and Post-test sections provides a measurement of the aftereffects of training. For a proper comparison of the Pre- and Post-tests, the two sections should be as similar as possible. It is possible, however, that subjects might re-adapt to the immediate feedback during the Post-test, masking any aftereffect of training. To avoid readaptation to immediate feedback, only 5 trials were presented during the Post-test. For each subject, all 5 trials were at their "Top Speed" from the Pre-test.

2.3 Results and Discussion

Figure 3 shows the percentage of trials on which subjects successfully reached the street's end at their Top Speed for the Pre- and Post-tests. All groups showed a drop in the ability to drive to the end of the street, but this drop was only significant for the 230 ms group ($t(8)=9.238$, $p<0.0001$ for the 230 ms group; $t\text{'s}(8)<1.6$, $p\text{'s}>0.14$, for the remaining groups).

The maximum speeds that subjects were able to successfully complete during the Pre-Test were 90.72, 99.36, and 99.36 km/h for the 130 ms, 230 ms, and 430 ms delay groups, respectively. These speeds do not differ significantly ($t\text{'s}(8)<1.6$, $p\text{'s}>0.1.4$), indicating that the 3 groups have roughly similar driving abilities at the onset of the experiment. The results for the three delay groups are discussed separately in more detail below.

2.3.1 130 ms delay group

Subjects in the 130 ms delay group had little trouble navigating the streets during training, and the delay training did not significantly effect their ability to reach the street's end when the delay was removed. The street completion metric, however, is not particularly sensitive. It is possible that subjects had more difficulty controlling the car during the Post-test, but this loss of ability was not sufficient to force them off the road. A more subtle decrease in the ability to accurately control the virtual car should show up, however, as a decreased ability to stay in the proper lane. To

[1] In a shaping procedure, it is important that the initial task not be too difficult and that the increase in difficulty between subsequent levels of training not be too great. To ease the difficulty of the initial task, a slower speed (14 m/s) was used in addition to the 4 speeds from the Pre-test.

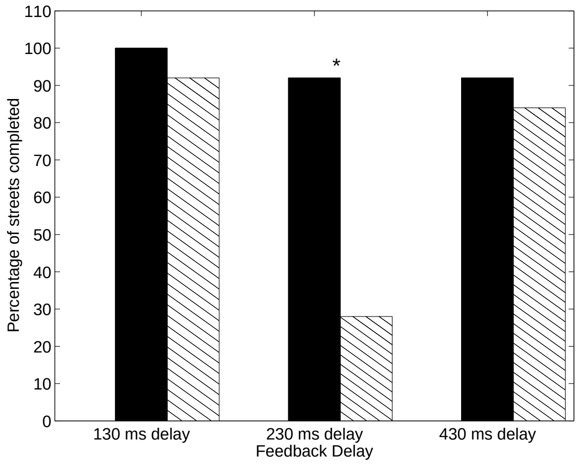

Figure 3: Results from Experiment 1. The average number of streets completed during the Pre- and Post-test at each subjects' "Top Speed" is plotted for the three delay groups. The solid bars depict Pre-test performance and the striped bars depict Post-test performance.

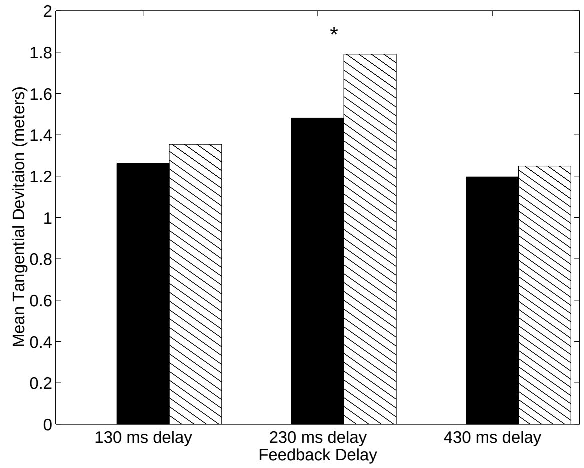

Figure 4: Tangential deviation between the virtual car's actual location and the center of the assigned lane. The solid bars depict Pre-test performance, and the striped bars depict Post-test performance.

examine for these less catastrophic changes in driving ability, we calculated the mean tangential deviation of the path traced by the car from the center of the assigned lane. This was done only for those trials that were presented at a subject's Top Speed, as that was the only speed that was present in both the Pre- and Post-tests. The results, averaged across subjects, are plotted in Figure 4. While there is a slight trend for subjects to have more difficulty staying in their lane in the Post-test, this increase is not significant ($t(48)=1.1984$, $p>0.23$). Learning to drive with a 130 ms delay did not impair performance without a delay.

One potential reason for the lack of a negative aftereffect is that a 130 ms delay is quite similar to immediacy, at least for the present task. It is worth noting that real cars do not respond immediately (inertia and various plant dynamic factors introduce delays). Thus, although the delay involved in real cars is less than 130 ms, it may be sufficiently similar that previous driving experience generalizes to a 130 ms delay. This possibility is explored in Experiment 2.

2.3.2 230 ms delay group

Every subject demonstrated a sharp drop in performance when the delay was removed. Street completion was between 40% and 80% lower in the Post-test than for the same speed during the Pre-test, with the average drop being 64%. Since subjects experienced a significant drop in their ability to stay on the road during the Post-test, it is not surprising that there was also a significant decrease in their ability to stay within the assigned lane ($t(48)=3.5207$, $p<0.001$). The lack of decrease in performance for the 130 ms group argues persuasively that the negative aftereffects found in the 230 ms group are not due to fatigue.

These results are very similar to those that Cunningham et al. (2001) found for performance on a simple, top-down view, obstacle avoidance task with a 250 ms delay. Interestingly, the average size of the negative aftereffect is remarkably consistent between the two experiments (64% and 52%, respectively).

2.3.3 430 ms delay group

There was little change in performance between the Pre- and Post-tests, either in the ability to stay on the road ($t(8)=0.8944$, $p>0.39$) or in the ability to stay within their lane ($t(48)=0.7693$, $p>0.44$). A look at performance during training provides an explanation: Subjects did not learn to drive with a delay. Four of the five subjects failed to make it to the end of the street even once. If subjects did not learn to perform the task with a delay, there is little reason for training to affect Post-test performance. One subject showed some proficiency at the task during training, and actually managed to complete training for the slowest speed (14 m/s). This subject showed a 40% drop in completion rate during the Post-test. This suggests that to the degree that subjects can learn to drive with a 430 ms delay, this improvement will produce a negative aftereffect when the delay is removed.

There are several likely explanations for subjects' low performance during training with a 430 ms feedback delay. The simplest explanation is that 430 ms is simply too large to adapt to. It is also likely, however, the lowest speed presented in the Training section was too difficult. Notice that the larger the delay is, the more difficult a given speed is (i.e., the earlier one would need to turn). Thus, an initial task that is easy for 230 ms (at 14 m/s, subjects only have to turn 2.8 m early on the 10 m wide road), might be too difficult for 430 ms (where subjects need to turn 6.6 meters early). As mentioned above, learning can be prevented in a shaping procedure when the initial task is too difficult. Perhaps subjects can learn to drive with a 430 ms delay if the initial task was made easier. This possibility is explored in Experiment 2.

3 Experiment 2

3.1 Introduction

Experiment 1 found that sensorimotor adaptation to intersensory temporal discrepancies can occur in a driving task. The specificity of temporal adaptation is, however, still unknown. Of particular importance is whether training on a single street improves performance on other streets. To examine this issue, Experiment 2 was divided into 3 sections (Baseline, Training, Generalization). Subjects were presented with four streets during the Baseline section of the experiment. This provides an initial measure of how good subjects can drive with a particular delay magnitude (either 130, 230, or 430 ms). They were then trained on a different street with the same delay. In the third section (Generalization) they were re-tested with the same delay on the four streets from the Baseline section, as well as on four new streets. If temporal adaptation is not specific to the training street, one would expect to see higher performance in the Generalization section than in the Baseline. Moreover, if the degree of novelty of a street is important, then subjects should be better during the Generalization section on the streets they saw in the Baseline section than on the four completely new streets. While each street in the Baseline was seen only 4 times (once at each of the 4 speeds), recent work on the memorization and replication of turns has shown that subjects can accurately reproduce a sequence of 3 turns after only 2 repetitions (von der Heyde, 2000). So, one might refer to the Baseline streets as “old” and the four new streets as “novel”.

The results of Experiment 1 also suggested that temporal adaptation can only occur for a tight range of delay magnitudes. It is possible that a 130 ms delay may be too similar to real world driving to affect driving performance. If that is the case, then Baseline performance (i.e., performance without training) should be the same whether feedback is immediate or delayed by 130 ms. The failure to adapt to a 430 ms delay may have been due to the initial difficulty of the task. If that is the case, then the addition of slightly slower speeds should allow adaptation to occur.

3.2 Method

3.2.1 Subjects

Sixteen subjects participated in the experiment. One subject developed simulator sickness, and did not complete the experiment. Their data have been eliminated from analysis. Subjects were randomly assigned to one of the three delay conditions until each condition had a total of 5 subjects.

3.2.2 Apparatus

The apparatus was the same as in Experiment 1.

3.2.3 Stimuli

The stimuli were identical to those used in Experiment 1, except that eight additional streets were used (See Figure 4). All of the streets were 10 meters wide and of similar complexity.

3.2.4 Procedure

The procedure was similar to that used in Experiment 1. During the Baseline section, four streets (Figure 5 a-d) were presented once at each of the four speeds, for a total of 16 trials. The Training section used the same street as in Experiment 1 (Figure 2). The Generalization section presented eight streets (Figure 5 a-h) once at each of the four speeds, for a total of 32 trials.

Simulator sickness was an issue in Experiment 1, with about 25% of the subjects being unable to complete the experiment. While a discussion of simulator sickness is beyond the scope of this article, it is generally accepted that a conflict between the visual and vestibular perception of acceleration is one major cause. In Experiment 1, the high speeds and sharp corners produced a large visual angular acceleration, but there was no corresponding vestibular simulation. To reduce this conflict, slower speeds were used in Experiment 2. Specifically, the 130 and 230 ms delay groups were presented with speeds of 16, 18, 20, 22, and 24 m/s, while the 430 ms delay group was presented with speeds of 12, 14, 16, 18, and 20 m/s. As with Experiment 1, the slowest speed was only presented during the Training section. The new set of speeds, which were chosen based on Experiment 1, should not only reduce the incidence of simulator sickness, but should provide a tighter measurement of subjects' driving abilities (since the speeds were more tightly clustered).

3.3 Results and Discussion

In all 3 groups, performance in the Generalization section was better than performance in the Baseline section (see Figure 6), demonstrating that training with a delay on one street improves performance with the same delay on novel streets. Furthermore, there was

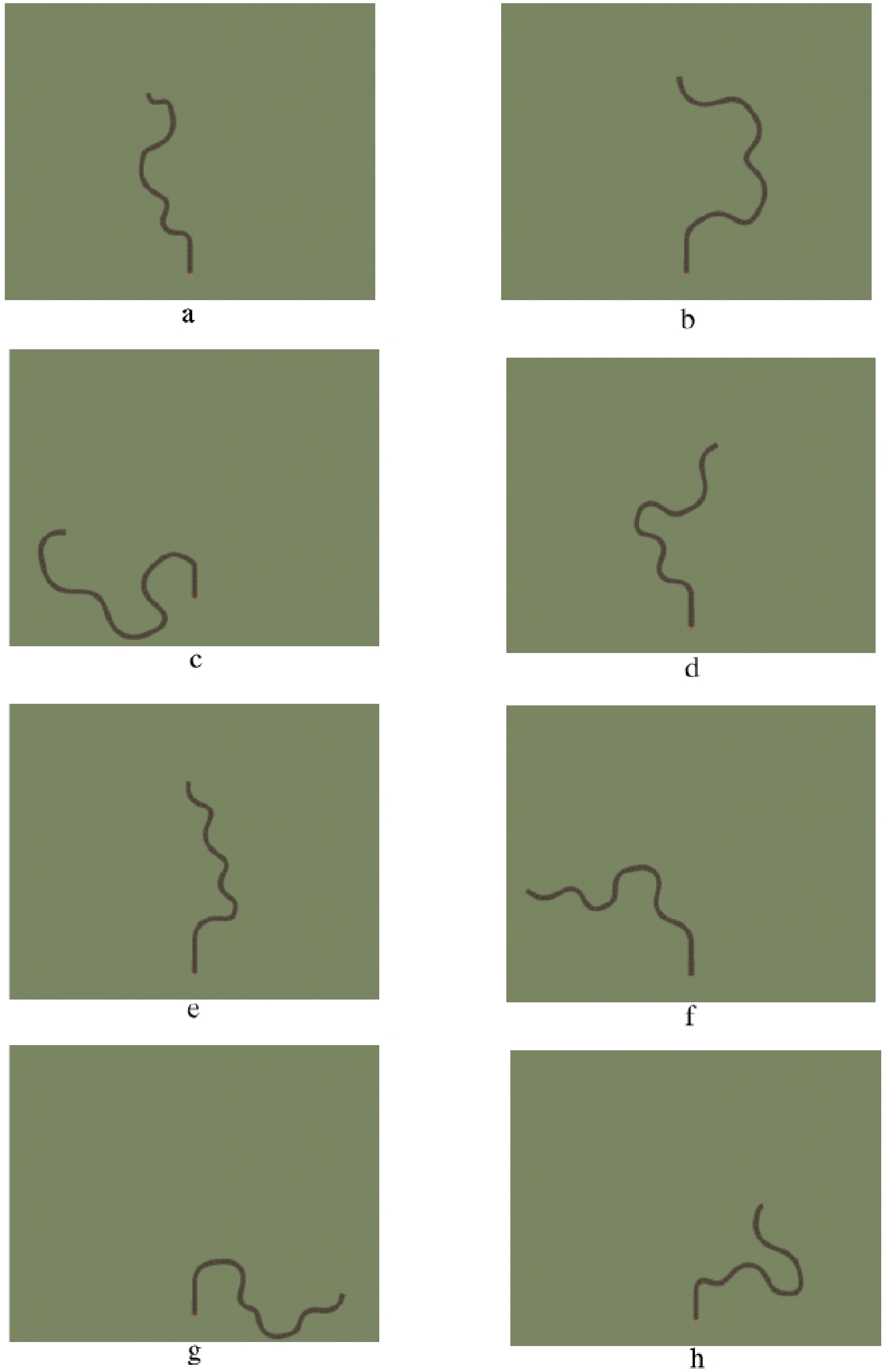

Figure 5: Eight of the streets used in Experiment 2. Streets a - d were used in the Baseline and Generalization sections. Streets e - h were used only in the Generalization section.

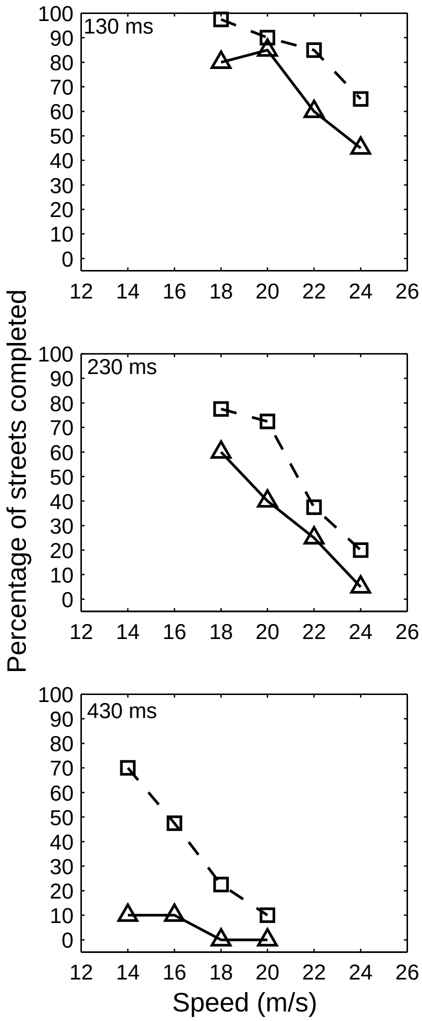

Figure 6: Results of Experiment 2. The solid line depicts the percentage of streets that were successfully completed during the Baseline section, and the solid line for the Generalization.

no difference between the "old" and "novel" streets in the Generalization section, suggesting that the degree of novelty of a street does not have a great influence on generalization.

As expected, fewer people developed simulator sickness than in the Experiment 1. This not only confirms the role played by intersensory acceleration differences in simulator sickness, but suggests that delayed feedback does not itself seem to cause simulator sickness.

3.3.1 Is a 130 ms delay different than no delay?

Figure 7 depicts a comparison of the Baseline performance with a 130 ms delay to average Pre-test performance (with no delay) from Experiment 1. As can be clearly seen, subjects performed worse in the 130

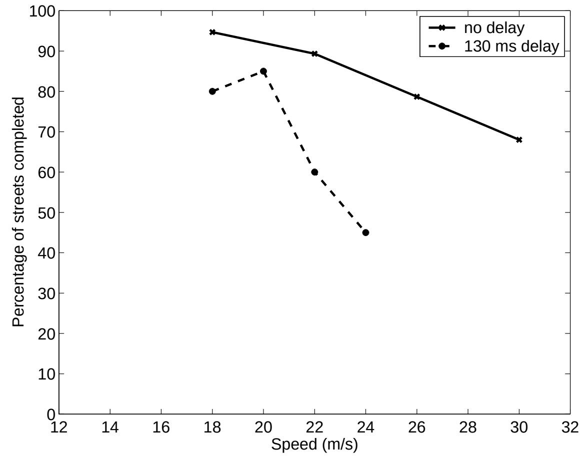

Figure 7: Comparison of untrained performance with 130 and immediate feedback.

ms delay condition. Delaying feedback by as little as 130 ms does impair driving.

3.3.2 Can humans adapt to a 430 ms delay?

Adding a slower speed during training allowed subjects to adapt to a 430 ms delay. All subjects completed the 14 m/s speed during training, whereas only 1 subject could do this in Experiment 1. Indeed, all 5 subjects in Experiment 2 had some success at a speed of 18 m/s, whereas no subject in Experiment 1 could complete a street at this speed. Furthermore, two subjects completed the fastest speed during training (20 m/s) with little difficulty. These results contrast strongly with those from Experiment 1, and provide evidence that the inability of subjects to adapt to a 430 ms delay in Experiment 1 was due to an ineffective training procedure.

4 General Discussion

Strict temporal contiguity between an action and its consequences is not necessary for rapid and accurate interaction with the world. While the introduction of a delay between action and consequence does impair behavior, a few minutes of the proper experience improves performance considerably (even for delays as large as a half a second). While Cunningham et al. (2001) showed that training can return performance with a delay to non-delay levels of skill, performance in the present experiment was not as comparable across the delay and immediate conditions. One likely cause of the lower amount of improvement found in the present experiment was the shorted training section. Subjects in the earlier work received considerably more practice in the delay condition (including a greater number of number of speeds, and a greater number of trials per speed). Moreover, the speeds in the present experiment were more widely spread (providing for a coarser gradient between speeds during training). As with any shaping procedure, large changes in difficulty between subsequent levels of training can reduce the effectiveness of training. Along those lines, Experiment 2 provided strong evidence that even small changes in the relative difficulty of the training procedure can yield large changes in the amount of learning obtained. It seems likely, then, that more training would return driving performance with a delay to normal levels.

The present results, combined with those of Cunningham et al., make it clear that the improvement found during training is the result of sensorimotor adaptation. In his classic book, Welch (1978) defines adaptation to perceptual rearrangements as, "a semipermanent change of perception or perceptual motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors in behavior induced by this discrepancy" (p.8). Not only is this definition met, but the pattern of results obtained with Temporal Adaptation is strikingly similar to that obtained with Spatial Adaptation: (a) an intersensory discrepancy impairs performance at first; (b) a few minutes of exposure to the consequences of the discrepancy improves performance; (c) practice without being exposed to the consequences of the discrepancy (e.g., by allowing subjects to slow down in the case of a temporal discrepancy or by not showing the subjects their hand in the case of Spatial Adaptation) does not lead to improved performance; (d) adaptation to the discrepancy produces a strong negative aftereffect; (e) adaptation to the discrepancy seems to result in a change in the perceived relationship between the two sensory modalities; and (f) adaptation generalizes to novel variations of the task.

It is known that neural pathways within and across modalities often differ in processing speed (Bolz, Rosner, & Wässle, 1982; Sestokas & Lehmkuhle, 1986) and several models on how intersensory integration might compensate for these temporal offsets have been proposed (Baldi & Meir, 1990; Eckhorn, Reitboeck, Arndt, & Dicke, 1988; Grossberg & Grunewald, 1997; König & Schillen, 1991; Singer, 1996). While too little is yet know about Temporal Adaptation to provide a detailed model, it is clear that existing models of temporal synchronization need to go beyond merely compensating for existing intersensory offsets. They must also be flexible enough to adjust to changes in the intersensory offset.

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