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The influence of perceptual speed regulation on speed perception, choice, and control: Tunnel wall characteristics and influences

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Abstract

The present work sought to determine if the type of visual pattern and presence of texture applied to transportation tunnel walls differentially affected driving performance. Choice of speed and speed control were measured with 32 participants who drove through a simulated transportation tunnel environment. Participants experienced three visual patterns consisting of vertical segments that decreased, increased, and remained a constant width throughout the length of the tunnel. Participants also drove a baseline control condition in which no visual pattern was present. Each of these conditions was presented either with or without a homogenous texture. When compared to the baseline condition, results indicated drivers gradually decreased speed when exposed to the decreasing width visual pattern and increased speed with the increasing width visual pattern. The presence of texture served to attenuate overall driving speed. Results suggest drivers' perception of speed and their subsequent response to such perceptions were modified by the visual pattern and texture expressed on the tunnel wall. The evident speed control opportunities afforded to the traffic engineer are discussed.

Keywords: Speed maintenance; Speed perception; Tunnel; Visual perception; Speed regulation

1. Introduction

Maintaining correct speed continues to be a challenge to many drivers as attested by the fact that in 2003 in the United States speeding was a contributing factor in 31% of all fatal crashes. The cost associated with such behaviors has been estimated at $40.4 billion (National Highway Transportation Safety Administration, 2003). It is due to the pervasiveness of this form of behavior, its effects in terms of loss of life and injury, and high societal financial cost associated with inappropriate speed maintenance that it is necessary to identify potential speeding countermeasures and better understand the nature and extent of their influence. The capacity to influence drivers' ability to maintain proper speed in various environments is also important from a theoretical standpoint. The identification of the nature and extent of those elements within typical driving environments that influence drivers' perception of speed and subsequent speed choice can be employed to better understand the general relationship between perception and action as evidenced in allied areas of research (Hancock and Manser, 1997; Manser and Hancock, 1996). This information can then be employed in the development of accurate predictive models of overall human performance for applications in realms beyond transportation. Practically, the information gained and the models developed from theoretically motivated research applicable to real-world driving environments can facilitate the design of roadways that promote optimal levels of traffic flow and safety. Examples of these types of projects can be found in work conducted on various topics such as driver perception and stopping sight distances (Fambro et al., 1998; Krammes et al., 1996) and the association between driver eye height and roadway design (Fitzpatrick et al., 1998). It is through the combination of theoretically motivated research and practical application that a valid and useful investigation is possible into speed regulation countermeasures for the purpose of creating safe driving environments.

Countermeasures to regulate vehicular speed most often included changes to the physical features of the driving envi-

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ronment to address the ability of drivers to achieve and maintain criterion speeds. These manipulations can be classified as static forms firstly which include various examples such as roundabouts implemented to slow drivers and improve safety (Retting et al., 2001) and rumble strips employed to warn drivers of the need to slow (Fitzpatrick et al., 2002). Secondly, dynamic countermeasures include examples such as speed signs informing drivers of their current speed relative to a criterion speed (Rose and Ullman, 2003) and even public safety personnel placed at locations where drivers exhibit frequent speed violations. Each of these forms of countermeasures has utility but the major drawbacks are the high cost and effort associated with their installation, use, and long term maintenance and operation.

In light of the notion that visual perception is a significant source of information for the driver (Sivak, 1996) and that perception plays an influential role in driving (Schiff and Arnone, 1995, pp. 1–27) it is logical to expect direct manipulations of the environment that influence visual perception would be associated with and result in changes in drivers' ability to achieve or maintain criterion speeds. Previous work in this area has typically manipulated the spacing and width of a series of transverse bars called pavement patterns, typically applied to the surface of roadways. Pavement patterns have also been placed on the walls of driving environments for visualization purposes (Carmody, 1996) and it is due to the multi-faceted nature of these visual devices that they are referred to in the current work as visual patterns. Visual patterns are manipulated so their width is reduced in a linear fashion across a section of roadway such that, if a driver maintained a criterion speed, the rate at which the edges that form the intersection point between transverse bars would pass the driver at an increasingly higher rate. Presumably, the driver would perceive the gradually increasing edge rate as a gradual increase in vehicle speed and, as a result of the motivation to maintain a pre-determined speed, they would slow their vehicle. For the purpose of the current work we identify this notion as "perceptual speed regulation" (PSR) because of the significant role perception and action play on the ability to regulate speed. Some of the earliest laboratory work examining PSR was conducted by Denton (1966, 1976, 1980). The general methodology in several of the experiments was to allow participants to drive a low-fidelity driving simulator through environments where various visual patterns existed. While being exposed to these visual patterns participants were asked to reduce their speed by one half. Results of these studies generally indicated different visual patterns differentially influenced drivers' perception of speed and their subsequent ability to achieve the intended goal.

The positive findings in the laboratory appear to be confirmed by work in field settings albeit the magnitude of effect was inconsistent across testing circumstances. The Newbridge Roundabout on the M8 in Scotland was experiencing a high rate of crashes due to excessive entrance speeds. After Denton (1980) applied the visual patterns employed in earlier laboratory work to the area preceding the roundabout mean entrance speed reduced by 12.8 km/h. Argent (1980) also reported a substantial effect on average speed reduction (combined night and day) of 10.3 km/h via the application of visual patterns in advance of a sharp curve. Ito (1995) (as cited in Griffin and Reinhardt, 1996) also reported significant reductions in crash rates ranging from 14.5% to 73.7% at six sites in Japan associated with the deployment of visual patterns in the shape of chevrons. While a significant reduction in crash rates is important, the lack of specific speed change information reported in some of these studies does not allow for a meaningful and consistent comparison of the nature and extent of the effectiveness of the pavement patterns themselves. More recently Drakopoulos and Vergou (2003) report that at the end of a section of relatively straight expressway leading into a curve the application of visual patterns in the form of chevrons reduced speeds by 24.14 km/h. However, these results are contrasted by other studies which have shown relatively small effects due to the application of the visual patterns. For example, a small but significant 3 km/h average speed reduction was reported (Zaidel et al., 1986) when a visual pattern was applied to the approach of an intersection while an average speed reduction of 2.02 km/h was observed when similar patterns were applied to the exit ramp of a freeway (Maroney and Dewar, 1987). While these findings do indicate positive utility for visual patterns it is clear the magnitude and extent of the effect is inconsistent and more importantly the crucial controlling elements of the visual display remain largely unidentified.

While results of previous PSR research appear to be promising albeit inconsistent the utility of this approach has not been adequately proven as a result of several limitations relative to research methodology and visual figure-ground considerations. The most significant research technique limitation is associated with the potential presence of a Hawthorne effect (Landy, 1989, pp. 443–449) that suggests performance changes may be due simply to the presence of an experimental manipulation which motivates individuals but is not associated with any definitive underlying information-processing mechanism. Previous research has typically employed a design in which driving performance before and after installation of the visual patterns was compared. While this design can detect pre-post performance differences it cannot determine if the changes were due to PSR, due to warning and startle effects, or elicited by the mere motivating presence of the novel visual patterns. The latter explanatory hypothesis has been suggested previously by Maroney and Dewar (1987) and Griffin and Reinhardt (1996, p. 48). Distinguishing why such effects occur is important because driving performance models can be developed more easily, be more accurate, and provide greater applicability to the design of real-world roadway environments if they are based on factors that can be uniquely identified, distinguished, and predicted.

A second methodological limitation may be associated with regression toward the mean (Cohen and Cohen, 1983). In the current context a reduction in a high rate of crashes or speed from one measurement interval to another may be due simply to natural variation and not necessarily due to an experimental manipulation per se. As a result, a pre-post measurement technique instigated which observes changes in high crash rates or speeds may simply be detecting natural variations (i.e., decrements) in the magnitude of the effect between each measurement in time.

There exist several background considerations that have not been addressed adequately in previous research that may account for the statistically significant but perhaps not practically significant reductions in speed. One salient consideration is the field of view subtended by the visual patterns presented to participants. Several research efforts applying visual patterns to roadways have observed relatively small speed changes (i.e., between 2 and 10 km/h) (Argent, 1980; Maroney and Dewar, 1987; Zaidel et al., 1986) whereas other research efforts applying visual patterns to the entire field of view observed greater changes is speed (i.e., 12 km/h) (Denton, 1980). In light of allied research which has indicated the accuracy of subjective speed estimates (Osaka, 1988, pp. 45–54) and time-to-collision estimates (Cavallo and Laurent, 1988) decreases in restricted as compared to normal field of view conditions, it is not surprising the magnitudes of the effects for speed changes vary greatly depending on field of view size. It is because of this potentially significant impact of differing fields of view that there is a need to hold constant this variable to provide more reliable and accurate data regarding the influence of visual patterns alone on driving behaviors.

A second salient feature that has eluded research efforts relative to the perception of speed in land transportation environments is the presence of texture on surfaces to which a visual pattern is applied. Osaka (1988, p. 51) examined the influence of field of view in both day and night conditions on drivers' ability to estimate speed and indicated speed estimation was likely to suffer under nighttime, reduced illumination, or reduced contrast conditions as a result of the loss of an overall texture gradient. This observation suggests drivers actively use texture as a source of information for speed estimation and speed regulation and, as the salience of the texture increases, the information provided by the underlying visual patterns becomes less salient. Relative to existing research it may be possible the inconsistent findings may have been due to varying degrees of texture gradient and subsequent texture salience, a factor which remains uncontrolled in the majority of these studies.

Third, previous research has focused on speed as the sole behavioral outcome of PSR. While this is an important contributing factor to overall safety we contend there may exist additional behavioral variables that may be influenced by visual patterns and contribute to the overall level of safety in driving environments. For example, an increase in speed maintenance consistency or a marked decrement in the maximum accelerations exhibited by drivers would facilitate smooth traffic flow and decrease the propensity for inter-vehicle collisions due to the large speed discrepancies.

Given the observations we have made, there are four primary objectives of the present research effort: (1) to determine the nature and extent of the influence of visual patterns on drivers' ability to set and maintain speed, (2) to investigate whether texture applied to the driving environment serves as source of information which can be used to regulate speed, (3) to determine the underlying mechanism which subsume the effects of PSR, and (4) to address the research technique and background consideration limitations identified in previous research. The present experiment involved participants driving through a standard transportation tunnel while attempting to maintain a criterion speed. Four different visual patterns were applied to the tunnel walls with each having texture and no-texture counterparts. Behavioral outcome measures were categorized into speed choice and speed control to better characterize the nature, extent, and underlying mechanisms of visual patterns on PSR.

2. Method

2.1. Participants

Participants in this study were 14 females and 18 males between 18 and 27 years of age (mean = 20.28, standard deviation = 1.84) recruited from the staff and student body at the University of Minnesota. These participants were divided into two groups consistent with the texture pattern applied to the tunnel walls. Within the non-texture between-subject group there were seven females (age range = 19–22, mean = 20.86, standard deviation = 1.35) and eight males (age range = 18–23, mean = 20.13, standard deviation = 1.73) while in the texture condition there were seven females (age range = 19–27, mean = 20.86, standard deviation = 2.79) and 10 males (age range = 18–22, mean = 19.6, standard deviation = 1.35). Participants did not receive any monetary compensation or class credit for their involvement. Participants possessed a valid state of Minnesota or Wisconsin driver's license, 20/40 vision or corrected to 20/40 vision, and possessed no known physical or cognitive limitations which might have affected performance in this study.

2.2. Apparatus

2.2.1. Driving environment simulator

The present study was conducted in a wrap-around driving environment simulator (DES) to maximize experimental control and to reduce the potential for intrusion of superfluous variables. The DES consisted of a spherical steel and wooden dome structure which, onto the interior walls, were affixed eight white fiberglass screens. Each screen was 250 cm in height extending up from the floor and was synthesized with the adjacent screens so it appeared as if there was a single screen wrapping 360° around the driver and vehicle. The driving scene presented to participants was created by Coryphaeus Easy Scene® computer software, generated by a Silicon Graphics Incorporated® Onyx computer (Reality^2 engine), and projected through three Electrohome ECP-3100® projectors to the curved wall of the DES. The three images projected to the wall were synthesized to create a single image subtending a field of view 165° horizontally and 55° vertically for the participant. Participants sat in the driver's seat of a full-sized 1985 Acura Integra RS positioned in the center of the DES and possessed complete control of acceleration, braking, and steering. A national instruments analog to digital converter operating within a Dell 100 MHz computer collected x, y, z, roll, pitch, and yaw data from the vehicle and forwarded this information to the Silicon Graphics Incorporated® Onyx computer. The data was then employed to update the driving scene at a continuous rate of 30 frames per second. High frequency vibrations were imparted to the vehicle along with subdued engine noise; each changing according to the speed of the vehicle. The configuration of the DES was consistent with calls for increased ecological validity in research to facilitate the generalization of results to real-world settings (Chapanis, 1988) and the need to include processes (i.e., behavioral, cognitive, and perceptual) that typify real-world driving environments in simulation based research (Schiff and Arnone, 1995). Collectively, the components of the DES provided realistic representations of the underlying behavioral, cognitive, and psychological processes necessary for visual perception and speed research. However, as we have indicated elsewhere (Hancock and Manser, 1997; Manser et al., 1997) the use of simulation as a tool to gauge driver performance metrics may itself influence performance. It is because of this influence that we urge the reader to exercise due caution in extrapolating results of this project to real-world situations. In addition, while the results of simulation based research can generalize strongly to real-world scenarios final testing in real-world scenarios is encouraged.

2.2.2. *Driving environment*

The driving environment employed in all experimental conditions was representative of a typical roadway segment consisting of a three lanes 0.86 km in length. Each lane was 2.43 m wide, colored light gray, and separated from the adjacent lane by a solid white line. Shoulders on each side of the roadway were 0.91 m wide and colored dark gray. There were no elevation changes throughout the length of the roadway and the entire length of the roadway including the tunnel section was straight. The final 0.48 km of roadway was surrounded by a tunnel 7.62 m high and 9.14 m wide. The ceiling of the tunnel was colored brown with no markings. A tunnel was chosen due to its ability to isolate visual factors and the fact that previous indications suggest speed perception could be manipulated successfully in this environment (Carmody, 1996).

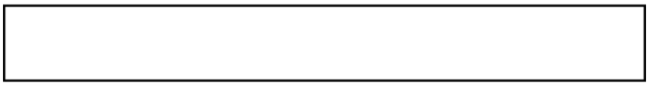
2.3. *Procedures*

After completing the Human Subjects Consent process, participants sat in the driver's seat of the Acura Integra and were given the specifics of the experiment. Instructions indicated they would be starting each drive parked in the center lane of a three lane roadway, they were to accelerate to a criterion speed of 80.47 km/h prior to the tunnel entrance, maintain the criterion speed throughout the tunnel length, and not change or move to adjacent lanes. The task and criterion speed were selected because they were representative of actions and goals that drivers typically encounter in driving environments. Participants were also instructed that the speedometer would cease to operate as the vehicle passed the tunnel entrance. Removing the speedometer from use prevented participants from employing that device for speed regulation. The remaining sources of speed information included visual perception which was the primary source of speed information and high frequency vibrations and subdued engine sounds which were considered tertiary sources of speed information. The presence of the vibrations and sounds as a potential confounding factor was regarded as minimal because if it was found that visual patterns can significantly impact driving performance this finding becomes increasingly salient due to the potential of the sounds to serve as an additional information source and subsequently counter or attenuate the influence of visual patterns thus reducing the probability of finding differences between conditions.

Thin to wide stripe condition

Wide to thin stripe condition

Thin to thin stripe condition



No stripe condition

Fig. 1. A depiction of the four visual pattern conditions.

One half of the participants performed 10 trials in each of four experimental conditions with all 40 trials presented randomly in order to avoid presentation order confounding effects. Visual patterns applied to the tunnel walls differentiated each of the four experimental conditions which consisted of: (1) wide to thin (CWT), (2) thin to wide (CTW), (3) baseline thin to thin (CTT), and (4) a control condition with no-pattern (CBA). A figure depicting the general visual pattern conditions is presented in Fig. 1 with screen-shots of the CTT and CBA conditions presented in Figs. 2 and 3, respectively. The walls of the CWT consisted of broad vertical black and white segments extending from floor to ceiling 30.48 m wide at the tunnel entrance and decreasing gradually in width using a linear function to

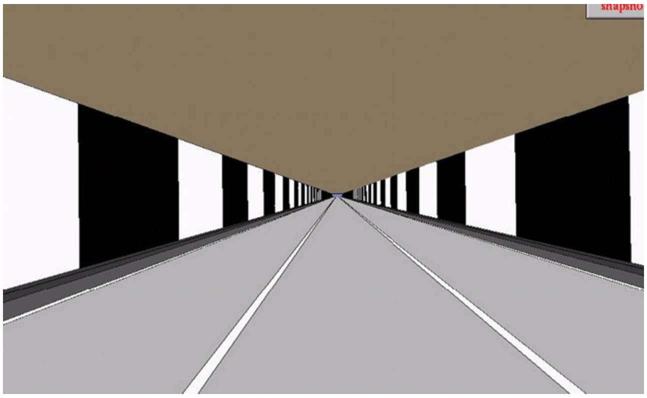


Fig. 2. A computer screen-shot of the thin–thin experimental condition presented to participants. Note: the image presented to participants in the driving environment simulator covered 165° field of view horizontally and 65° vertically.

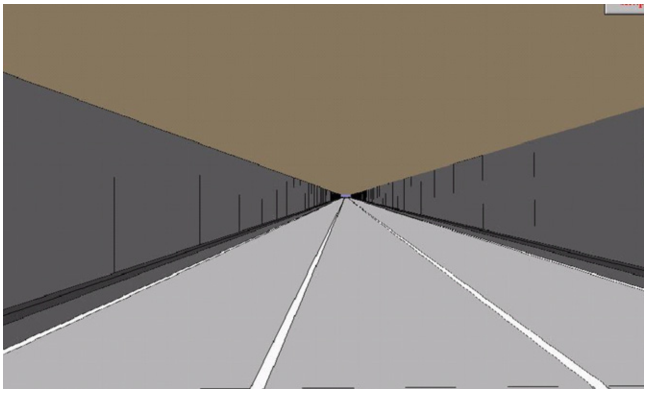


Fig. 3. A computer screen-shot of the no-pattern baseline experimental condition presented to participants. Note: thin vertical lines appearing on the tunnel walls are an anomaly of process by which this screen-shot was captured. Note: the image presented to participants in the driving environment simulator covered 165° field of view horizontally and 65° vertically.

7.62 m at the tunnel exit. As participants drove through the tunnel attempting to maintain a constant criterion speed, they experienced a gradual increase in the number of segments (i.e., edges formed by adjacent black and white segments). The CTT was a baseline condition that depicted 7.62 m wide segments throughout the tunnel length while the CBA was a control condition that depicted walls without visual patterns. To determine if texture is employed as a source of visual information, as suggested elsewhere (Osaka, 1988, p. 51), the second half of participants performed 10 trials in each of the four experimental conditions, however, on the walls in each condition there was an approximately 50% transparent homogenous texture. If texture itself is a salient speed regulation cue the effects of visual patterns on perception and subsequent action would be diminished or non-existent.

2.4. Formal hypotheses

We hypothesized (H1) the CWT condition would promote a perception of speed gain and, through the interaction between visual perception and action, an effect for visual pattern on driving behavior would be realized in the form of a progressive decrease in speed throughout the tunnel length. Furthermore, the design of the CWT was equivalent to previous visual pattern research manipulations and thus could provide replicating evidence of the existence of PSR. CTW was identical to CWT except the pattern from tunnel entrance to exit was reversed (i.e., thin to wide). Our second hypothesis (H2) was that of a direct inverse of the first, indicating drivers viewing this condition would perceive themselves as slowing down below the criterion speed and thus would compensate by gradually increasing their speed. A systematic increase in speed in this condition would serve to confirm several PSR related tenets indicating changes in driving behavior were: (1) not due to the mere presence of an experimental condition as suggested by the Hawthorne effect, (2) not the result of a startle or warning effect, (3) not due to regression toward the mean, and thus (4) changes were due to an underlying process of visual perception. Furthermore these findings would suggest visual information can be altered to regulate both increasing and decreasing speed; a proposition not examined in previous research and an additional form of countermeasure which can potentially be employed by transportation engineers. Our third hypothesis (H3) suggests that as participants drive through the tunnel speed perception would not be altered due to the continuous width of stripes in the CTT condition or absence of visual patterns in the CBA condition. Subsequently speed itself would remain relatively constant. In addition, our fourth hypothesis (H4) indicates that in the CBA, given that no visual information may be used for speed regulation, such as provided in the CTT, it was expected that spontaneous variations in speed choice or control may occur. Data consistent with this hypothesis would provide further evidence to support the visual information explanation of observed effects. In light of the fact that allied research has indicated drivers will employ multiple sources of visual information when available (Hancock and Manser, 1997) this final hypothesis (H5) suggests speed choice and control will be influenced to a greater degree in the CWT and CTW when texture is not present. Due to the ability of texture to serve as a source of speed regulation information the effect for texture may also be exhibited as a general enhancement in the ability to maintain a criterion speed despite the influence exerted by visual patterns. Similar to the ability of drivers to use the demarcations between black and white segments to regulate speed in the visual pattern conditions the texture provided throughout the length of the tunnel affords drivers the opportunity to continually regulate speed and be influenced to a lesser degree by the underlying visual pattern.

2.5. Dependent variables

Dependent variables were collected via a system which defined five equidistant points throughout the tunnel (i.e., tunnel entrance, tunnel exit, and three equally spaced points in-between). These results were contrasted with a zone system in which the recorded dependent variables were averaged across each of four zones differentiated by the five points. These point and zone data collection systems allowed for a complete description of performance over time. The dependent variables were classified into speed choice and speed control to characterize thoroughly the influence of PSR. Speed choice describes aspects of the speed chosen by drivers through the tunnel and was defined by instantaneous speed (S) measured at each point, maximum speed (MS) attained within each zone, overall deviation in speed (absolute error of speed) (AES) within each zone, response bias in speed (constant error of speed) (CES) within each zone, and the number of times within each zone drivers implemented a speed reversal (i.e., a change from acceleration to deceleration greater than 0.25 km/h) (SR). Speed control describes variability in speed exhibited throughout the tunnel and was defined by the maximum acceleration rate (MA) observed within each zone, the maximum deceleration rate (MD) observed within each zone, and speed consistency (variable error of speed) (VES) within each zone. (For an in depth description of these forms of constant, absolute, and variable error measures, see Schmidt and Lee, 2005.) Each of the metrics within speed choice and speed control were considered independently. Speed choice and speed control metrics were considered because they have not been examined previously, can more accurately characterize speed behaviors throughout a tunnel environment, and would provide important information relative to real-world traffic flow and safety levels.

2.6. Design

All interactions and main effects were analyzed with the Wilk's lambda multivariate analysis of variance procedure[1] (WL). Speed (S) was analyzed in a $2 \times 4 \times 5$ (texture × visual pattern × point) WL multivariate analysis of variance with texture as a between-participant variable and visual pattern (CWT, CTW, CTT, and CBA) and point (one, two, three, four, and five) as within-participant repeated variables. The remaining dependent measures for speed choice and speed control were analyzed in a $2 \times 4 \times 4$ (texture × visual pattern × zone) WL multivariate analysis of variance with texture as a between-participant variable and visual pattern (CWT, CTW, CTT, and CBA) and zone (1, 2, 3, and 4) as within-participant repeated variables. Significant differences for main effects were distinguished using a Bonferroni post hoc paired comparison test to account for an increased number of analyses. Significant differences for interactions were distinguished using a WL for main contrasts and a Bonferroni post hoc paired comparison test. The alpha level for each comparison was set at .05. Partial eta squared (η^2) and observed power (OP) obtained from SPSS (version 12.0) are reported for all main and interaction effects in order to facilitate greater understanding of the results and to facilitate efforts of future research within this topic.

3. Results

Where tunnel entrance speed on a single trial was greater than or lesser than two standard deviations from the mean of all tunnel entrance speeds these data were considered outliers. Due to the fact that an outlying speed at the tunnel entrance would create outlying speeds throughout the remainder of the tunnel all driver speed data for the reminder of the trial were also removed prior to data analysis. Similarly, because speed data served as the basis for calculating subsequent dependent variables any data which was derived from an outlying speed were also omitted from data analysis in order to reduce possible confounding effects due to the inclusion of outlying data. Reported values reflect the removal of these outlying scores. All main and interaction effect information can be found in Table 1.

Table 1
Main and interaction effect data for each significant finding

Measure	Effect	WL	p	η^2	OP
Speed	Point	(4, 278) = 33.72	<.00	.33	1.00
Speed	Texture	(1, 361) = 10.32	<.00	.35	.89
Speed	Visual pattern × point	(12, 270) = 2.13	.02	.09	.94
MS	Zone	(3, 280) = 95.45	.01	.51	1.00
MS	Texture	(1, 282) = 10.66	<.00	.04	.90
AES	Zone	(3, 279) = 159.30	<.00	.63	1.00
CES	Zone	(3, 279) = 42.22	<.00	.31	1.00
SR	Zone	(3, 280) = 21.59	<.00	.19	1.00
SR	Texture	(1, 282) = 17.83	<.00	.06	.99
SR	Zone × texture	(3, 280) = 7.06	<.00	.07	.98
SR	Visual pattern × zone	(9, 274) = 1.96	.045	.06	.84
MA	Visual pattern	(3, 42) = 3.45	.03	.20	.73
MA	Zone	(3, 42) = 8.05	<.00	.37	.99
VES	Zone	(3, 279) = 167.02	<.00	.06	1.00

3.1. Speed choice

Results of the speed analysis indicated a main effect for point. The mean speeds for points one through five were 83.20, 84.63, 86.30, 87.05, and 88.30 km/h, respectively. Post hoc analysis indicated the speed at all points was significantly different from all others. Results indicated a texture main effect with the non-texture and texture condition means being 87.03 and 84.76 km/h, respectively. There existed a significant visual pattern by point interaction for S. Follow-up analyses on the interaction indicated significant differences between visual pattern conditions at measurement point five only, WL(3, 280) = 4.04, $p = .008$, $\eta^2 = .04$, OP = .84. Pairwise comparisons with the Bonferroni correction indicated significant differences between the CTW ($M = 89.86$) and CWT ($M = 86.19$), $p = .007$, and between the CBA ($M = 89.03$) and CWT ($M = 86.19$), $p = .046$. The interaction and paired comparison results indicate speed increased throughout the tunnel at a greater rate for the CTW and at a lesser rate for the CWT but it was at the final measurement point, the tunnel exit, the influence of visual pattern created significant differences between these two contrasting visual pattern conditions. In addition the paired comparison also indicated significant differences between the CBA and CWT conditions at the tunnel exit suggesting a wide to thin striping visual pattern can effectively suppress speed as compared to the lack of visual patterns. Collectively, these results provide initial support for H1, H2, and H3. The visual pattern by point interaction is illustrated in Fig. 4.

The MS analysis indicated a main effect for zone with the means for zones 1 through 4 being 85.24, 86.82, 87.28, and 89.72 km/h, respectively. Post hoc comparisons indicated each MS mean was significantly different from all others. The texture main effect indicated MS was higher in the no-texture condition (87.68 km/h) as compared to texture condition (85.22) which provides initial support for H5. The AES analysis revealed a main effect for zone with mean AES scores for each sequential zone being 1.28, 4.07, 5.94, and 7.97, respectively. Post hoc analyses indicated each mean was significantly different from

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[1] A priori, it was expected speed data would be constrained at the tunnel entrance as a result of participants' goal to achieve the criterion speed and would increase in variability by the tunnel exit due to natural variations in speed regulation abilities. This situation, as expected, created non-symmetry of data across point and zone resulting in the violation of the sphericity assumption (as indicated by a Mauchly's test of sphericity) thus necessitating the use of a MANOVA test in the form of a Wilk's lambda as opposed to a univariate test. The reader is referred to Keppel (1991, pp. 351–352) for a complete description of sphericity.

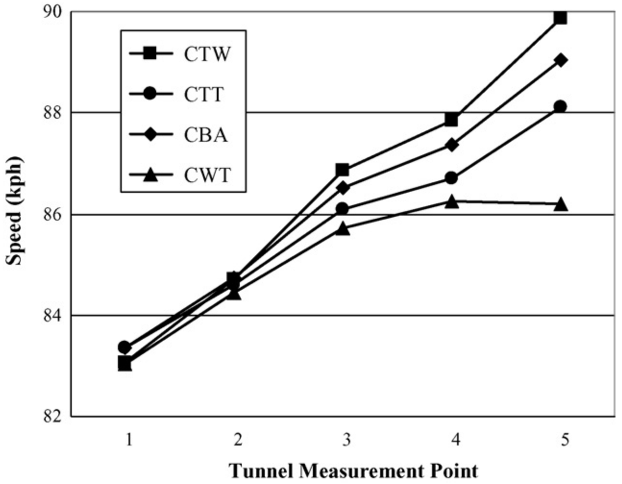

Fig. 4. A depiction of the visual pattern by point interaction for speed.

all others. This effect confirmed the total deviation from the criterion speed increased progressively throughout tunnel length thus providing initial support for H4. The CES main effect for zone indicated the bias in speed gradually increased throughout the tunnel length with the means for zones 1 through 4 being .53, 2.18, 3.40, and 4.75, respectively. Post hoc analyses indicated each mean was significantly different from all others.

The SR analysis indicated a main effect for zone that showed an increase in the average number of speed reversals throughout the tunnel. The average SR value for each zone was .25, .27, .16, and .58, respectively. Post hoc analyses indicated significant differences between SR means for zones 1 and 4, 2 and 3, 2 and 4, and 3 and 4. The SR main effect for texture indicated the average number of SR for the non-texture condition was greater ($M = .38$) than the texture condition ($M = .08$). There was a zone by texture interaction. Follow-up pairwise comparisons between the texture and non-texture conditions indicated texture resulted in significantly lower SR in each zones thus providing additional support for H5. The SR means for texture for zones 1 through 4 were .12, .08, .03, and .17, respectively, while the non-texture means for zones 1 through 4 were .38, .47, .29, and .99, respectively. A depiction of the texture by zone interaction is shown in Fig. 5. There existed a visual pattern by zone interaction. Follow-up analyses between visual pattern conditions at each of the four zones indicted no significant differences which was most likely due to the use of the stringent Bonferroni test. These results provide initial confirmation for H5. Fig. 6 depicts this visual pattern by zone interaction. No additional main effects or interactions were found for the speed choice analyses.

3.2. Speed control

The MA analysis resulted in a main effect for visual pattern indicating that CBA resulted in the greatest observed MA ($M = .39$), the CTW resulted in the second greatest MA ($M = .37$), and the CTT ($M = .29$) and CWT ($M = .27$) exhibiting similar MA rates. Post hoc analysis indicated the CBA and CWT were significantly different from each other, a finding consistent with H3. The main effect for zone indicated the MA observed in each zone decreased consistently from zones 1 to 3 and then increased slightly in zone 4. The MA means for zones 1 through 4 were .40, .36, .27, and .29, respectively.

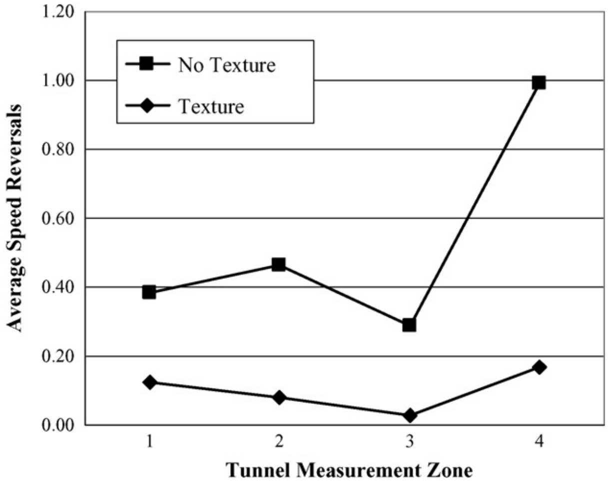

Fig. 5. A depiction of the texture by zone interaction for average number of speed reversals.

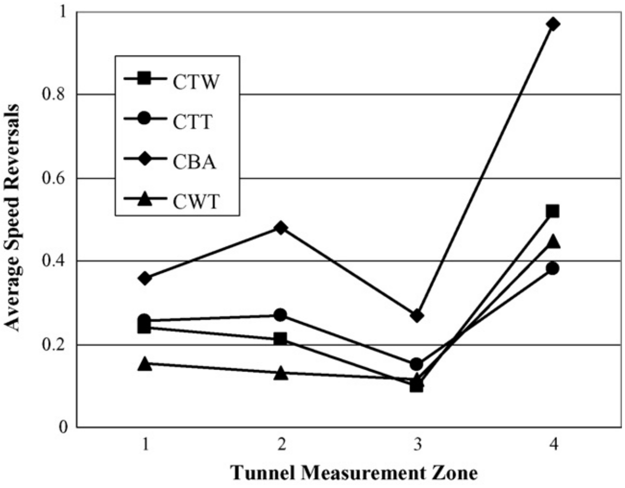

Fig. 6. A depiction of the visual pattern by zone interaction for average number of speed reversals.

For the VES, there was a significant main effect for zone. The mean VES scores for zones 1 through 4 were .88, .85, .39, and 1.06, respectively, with significant differences exhibited between all comparisons except between zones 1 and 2. These results indicate the variability of the speeds observed generally decreased from zones 1–3 and then experienced a dramatic rise in zone 4. No additional main effects or interactions were found for the speed control analyses.

4. Discussion

The ability to regulate speed and driver behaviors through the use of visual perceptual elements represents a significant tool that roadway engineers could apply in the design of transportation environments for the purpose of reducing excessive speeds, increasing problematic slower speed, improving traffic flow, and thereby increasing public safety. The primary finding of the present work was that speeds adopted by drivers could be influenced significantly by the application of visual patterns to a typical transportation environment. This was demonstrated primarily by the interaction between visual pattern and measurement point for the speed analysis within the speed choice construct. This interaction found that, despite the capacity to achieve a criterion speed before the tunnel entrance and being asked to maintain that speed throughout the tunnel length, drivers exposed to a visual pattern that gradually decreased in width responded by gradually decreasing vehicle speed throughout the tunnel when compared against the CBA and CTT conditions. This finding is consistent with our first hypothesis and confirms the conclusions of previous PSR research efforts. However, simply observing a reduction in speed associated with the presence of visual patterns fails to support fully PSR as the mechanism by which speed and driver behavior can be influenced as we have indicated previously. The interaction also indicated speed increased gradually throughout the tunnel when drivers were exposed to the CTW as compared to the baseline and control conditions, a finding consistent our second hypothesis and suggesting systematic modifications to visual perception elements in a transportation environment can result in systematic changes in speed by virtue of PSR alone. A hallmark of the capacity to generalize research results to a variety of real-world situations (Chapanis, 1988) is the ability of the differing visual patterns to produce predictable changes in behavioral outcomes. Indeed, results of this study may be applicable in many situations where humans are in motion and thus are not confined to ground-vehicular transportation alone. The implication of these findings is the existence of an underlying process consisting of a co-dependent relationship between visual perception of speed and perception of elements within the driving environment that makes PSR effective. Whether the underlying process is based in cognition or perception or a combination of each is important to determine in future work.

These findings exclude the possibility the other previously proposed factors we have disclosed may be responsible for PSR. If a Hawthorne effect was present there would exist consistent directional changes in speed for all conditions, null results across all conditions or, at the very least, null results across the CWT, CTW, and CTT conditions as a result of drivers responding simply due to the presence of an experimental condition. Startle and warning effects would be exhibited if drivers responded similarly to the three pattern conditions (i.e., slowing) or if there were significant differences between the CTT, where the visual pattern would promote a startle response, and the CBA, where no visual pattern would promote such a response. In addition, startle effects would be most evident in the first part of the tunnel and be evident in the zonal interaction in which zone 1 would be the exception compared to all others, but as is evident from the data, this simply does not occur. Each of these effects are now considered untenable due to the contrasting behavioral outcomes exhibited between the CWT and CTW conditions and the nearly identical behavioral outcomes of the CTT and CBA conditions. These findings which support hypotheses one, two, and three suggest changes in behavioral outcomes were due to the underlying processes of visual perception. While regression toward the mean cannot be discounted entirely a η^2 value of .33 and a ω^2 value of 1.00 strongly suggest the visual pattern by measurement point interaction for speed is a veridical finding.

The implementation of any speed countermeasure should occur only after a thorough investigation and understanding of the primary behaviors that may be influenced by the countermeasure. Traditionally, research examining visual patterns has focused on speed maintenance abilities. In contrast the current work examined an array of behaviors and found that additional behaviors, beyond speed maintenance, within speed choice and speed control were influenced by visual patterns. Results found an interaction between visual pattern and zone for SR indicating participants in each of the pattern conditions instigated changes to modulate speed at similar rates during the first half of the tunnel, the rate of these changes decreased after traveling halfway through the tunnel, and then the rate increased markedly near the end of the tunnel. In contrast when participants viewed the no-pattern CBA the rate of changes implemented was higher throughout the entire tunnel and that there was a significant rate increase over the three pattern conditions near the end of the tunnel. These results suggest two tendencies. First, and consistent with hypothesis four, the presence or absence of visual patterns can have a marked impact on drivers' consistency and rate of speed changes. In the visual pattern conditions participants may have implemented a feedback control loop consisting of implementation of SR in an attempt to maintain the criterion speed, speed perception, comparison of speed perception to perceived speed goal, and then implementation of SR. In contrast participants in the CBA omit the comparison stage because the impoverished visual information does not provide reliable or new information with which to make speed judgments. This results in more speed reversals. The second implication of these findings is the existence of an information source beyond visual pattern that provides utility for drivers. Research in allied areas has indicated drivers can reliably determine when an object will reach their position in space by perceiving the rate of expansion of an image of approaching object on the foveal portion of the retina and that this information becomes more salient the closer the object is to the driver (Manser and Hancock, 1996). It is postulated that in the current context when drivers had traveled more than 50% of the tunnel distance, the salience of the tunnel exit may have served as an object from which to estimate speed and speed consistency. This resulted in a significantly reduced SR frequency at zone 3 as compared to the previous and following zones, as indicated by post hoc analysis for the zone main effect. It is further postulated that because participants postponed any changes in behavior while they obtained speed information and compared it to current performance shortly during zone 3 near the tunnel exit drivers began to implement a variety of speed reversals to correct for any perceived deviations from the criterion speed. Participants with previous speed information in the form of patterns potentially felt they had been implementing changes continuously based on the feedback loop and only needed to implement a few additional SR to maintain the criterion speed. In contrast, participants in the CBA are using the exit information to their fullest advantage during their final moments in the tunnel as evidenced by the significantly higher SR rate observed of them at the end of the tunnel. The maximum acceleration rate was also significantly influenced by visual pattern. Findings indicated the least and greatest MA rates were observed in the CWT and CBA, respectively. Low MA for participants observing the CWT were expected as it was hypothesized PSR in that condition would generally result in participants slowing their vehicle while high MA for CBA is not surprising considering the large SR observed in this condition.

A second important finding from the present procedures indicated that texture placed on the walls of the tunnel had a marked impact on speed perception and subsequent driving behaviors. While results did not indicate the presence of texture differentially influenced speed in differing visual pattern conditions results did indicate speed and MS were attenuated when texture was present in the driving environment as compared to the absence of texture. Consistent with hypothesis five these findings provide support for the notion drivers were employing texture as a source of information to achieve their primary goal. In the current experiment the relationship between speed regulation and texture was also interactive with the salience of the tunnel exit as evidenced by two findings. The first of these indicated SR was generally consistent across zones 1 and 2, decreased slightly in zone 3, and then increased markedly in zone 4. This provides additional confirmation of the utility of the tunnel exit for providing speed-related information that participants use to readjust their speed in an attempt to maintain a criterion speed. The second finding provides a more detailed picture by indicating the rate of SR was greater for the texture condition in the first three zones and lesser in the fourth zone as compared to the non-texture condition. This finding suggests an active use of texture information to readjust speed in the early sections of the tunnel whereas at the end of the tunnel, where multiple sources of information (i.e., tunnel exit and texture) provided a richer perception of speed, drivers felt the need to implement slightly more speed readjustments to maintain the criterion speed. In contrast the rate of speed readjustments in the early sections of the tunnel in the no-texture condition was attenuated because poorer speed information led participants to believe they were adequately achieving their speed maintenance goal. However, as the perception of speed was gradually facilitated via the approach to the tunnel exit participants realized they were not adequately maintaining speed and implemented a series of speed readjustments greater in rate than the texture condition.

A third prominent finding indicated several variables within speed choice and control progressively changed with increasing distances through the tunnel. For speed choice, main effects for zone were found for S, MS, AES, CES, and SR. The gradual change in these variables was based primarily on speed changes and is consistent with previous observations in simulation. It has previously been demonstrated drivers' speed is higher without the use of a speedometer, as compared to the use of a speedometer, while driving in simulated tunnel environments (Törnros, 1998). Consequently, we anticipated there would be a gradual increase in speed after the speedometer ceased to operate at the tunnel entrance. Thus the central condition confirmed this known tendency. Results of analyses of speed control indicated zone main effects for MA and VES. The MA findings are not unanticipated as they are a logical consequence of a gradual increase in speed throughout the tunnel length. A consistent increase in VES was also expected due to low variability at the tunnel entrance being promoted by participants' goal to achieve a criterion speed before tunnel entry and becoming more varied through the tunnel length due to natural variations in behavior.

In conclusion results of the current work suggest PSR is a technique to be applied to tunnel environments, and perhaps restricted driving environments such as workzones, in an effort to influence speed choice and control. However, roadway engineers will need to be cognizant of the texture in any particular driving environment as a factor that may also influence perception of speed and subsequent driving behavior. That such patterning and texture should be permitted on tunnels in the United States, as they already are in many other countries, now appears justifiable and a systematic exploration of pattern effects may well help in this context and in many others where the kinematic tiger remains to be tamed (Haddon, 1970; Hancock, 2005).

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