



Using road markings as a continuous cue for speed choice

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ABSTRACT

The potential for using road markings to indicate speed limits was investigated in a driving simulator over the course of two sessions. Two types of experimental road markings, an “Attentional” set designed to provide visually distinct cues to indicate speed limits of 60, 80 and 100 km/h, and a “Perceptual” set designed to also affect drivers’ perception of speed, were compared to a standard undifferentiated set of markings. Participants ($n = 20$ per group) were assigned to one of four experimental groups (Attentional-Explicit, Attentional-Implicit, Perceptual-Explicit, Perceptual-Implicit) or a Control group ($n = 22$; standard road markings). The Explicit groups were instructed about the meaning of the road markings while those in the Implicit and Control groups did not receive any explanation. Participants drove five 10 km simulated roads containing three speed zones (60, 80 and 100 km/h) during the first session. The participants returned to the laboratory approximately 3 days later to drive five more trials including roads they had not seen before, a trial that included a secondary task, and a trial where speed signs were removed and only markings were present. The findings indicated that both types of road markings improved drivers’ compliance with speed limits compared to the control group, but that explicit instruction as to the meaning of the markings was needed to realise their full benefit. Although previous research has indicated the benefit of road markings used as warnings to indicate speed reductions in advance of horizontal or vertical curves, the findings of the present experiment also suggest that systematically associating road markings with specific speed limits may be a useful way to improve speed limit compliance and increase speed homogeneity.

1. Introduction

After 80 years of driver behaviour research, speed choice and speed management remain among the most challenging problems in road transport. The focus of the research described in this paper was to explore the potential for using road markings to indicate speed limits to drivers. The simulator experiment described in this paper represented a first step in comparing different types of centre and edge line marking schemes in terms of their effect on speed choice, compliance with speed limits, and comprehension of their meaning. If effective, road markings would provide continuously available information to drivers, and increase safety by reducing unsafe speeds and increasing speed homogeneity.

From a system perspective, speed management has significant consequences for both safety and efficiency. The Power Model suggests that high speeds increase both the severity and frequency of crashes (Elvik, 2013; Nilsson, 2004), and speed heterogeneity both increases the risk of crashes and decreases the efficiency or throughput of the road network (Garber and Ehrhart, 2000; van Nes et al., 2010).

From the driver’s perspective, speed choice can be difficult because

speed signs are only periodically present and in most jurisdictions the physical appearance of a road is not a reliable indicator of the enforced speed limit. Further, signs often go unnoticed by drivers, either because they are driving on “auto pilot” in a familiar environment or because their attention is focussed elsewhere (Charlton and Starkey, 2013; Harms and Brookhuis, 2016). In addition, even when speed limit signs are noticed, drivers may not find them credible due to a mismatch between the posted speed and the look and feel of the road (Charlton and Starkey, 2017a; Goldenbeld and van Schagen, 2007).

In a study of drivers’ compliance with reduced speed limits (from 90 to 70 km/h), drivers were found to increase their speeds as their distance from the last speed limit sign increased (Jongen et al., 2011). In driving scenarios where the speed limit signs were repeated less frequently, drivers were more likely to exceed the speed limit. The authors concluded that “speed control measures additional to speed limit signs are necessary to correctly manage speed” (p 782). Similarly, in a study of drivers’ speed limit beliefs and speed choices we found that residential roads where the speed limits had been reduced from 50 to 40 km/h were consistently judged as having 50 km/h speed limits, even though the participants had just seen the 40 km/h speed limit signs

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when driving the same roads in a video-based driving simulation and speed choice task (Charlton and Starkey, 2017a).

Although static speed limit signs are the conventional method of communicating speed limits to drivers, several alternatives have been explored. One combined field trial and simulator experiment explored continuous indication of the speed limit by adding either 0.5 m dashed lines adjacent to the road's painted edge lines every 50 m or painting the number "7" alongside the edge lines at 50 m intervals to indicate a reduction in speed from 90 to 70 km/h (Daniels et al., 2010). In this case, the additional markings did not improve speed limit compliance in either the field study or the simulator experiment. The researchers suggested that the markings may not have been sufficiently conspicuous for drivers to notice them, in spite of the presence of an information panel explaining the markings in the field trial. This was supported by the finding that fewer than half of the simulator participants, who were not told of the additional markings beforehand, reported noticing the additional markings when asked at the end of the experiment. Even when specifically identified to them, fewer than one third of the participants recalled seeing the additional markings on the simulated roads.

The presence of the additional markings, however, did result in a shift in drivers' lane position closer to the marked centre line, indicating that the additional markings were processed implicitly (perceptually) even if they were not attended to consciously (attentionally). When the simulator participants were asked to perform a secondary task (paced serial addition task; PASAT) while driving, speeds were reduced by about 4 km/h before the speed transition, particularly in the presence of the additional dashed lines (although two of the participants demonstrated extreme speeds of 120 km/h) (Daniels et al., 2010). Even though speeds were lower on the approach to the transition in the high mental workload condition, speeds at the point of transition to the 70 km/h zone were higher, speed reductions took longer, and the participants' final speed in the 70 km/h zone was 3–4 km/h higher compared to the low mental workload condition (i.e., without the PASAT).

Another suggestion has been to use colour coded road markings to indicate the speed limit such that roads with different speed limits would have different coloured centre and edge lines (Campagne, 2005). In this system, centre and edge lines would be painted red in low speed zones (35 km/h), yellow in moderate speed zones (50 km/h) and blue or green for higher speed zones (90 km/h and 130 km/h respectively). These colour coded road markings have not been tested to our knowledge, and issues such as night-time visibility of the markings and potential for confusion by colour blind drivers would need to be addressed.

One approach that has been tested used combinations of centrelines, edge lines, physical separation, as well as colours (Aarts and Davidse, 2008; Stelling-Konczak et al., 2011). The goal of these tests were to identify essential recognisability characteristics (ERC) that could be used to indicate different categories of road with different speed limits and overtaking permissions. In a simulator-based study comparing two recognisable road marking systems to standard road markings, the recognisable markings led to speeds reliably under the speed limit, with no difference between participants who had been told about the meaning of the markings before the simulated drive and those who had not been given any information beforehand (Aarts and Davidse, 2008). In a related study participants were asked to sort photographs of roads with and without the ERC markings and estimate the speed limit for the roads shown in the photographs (Aarts and Davidse, 2007). The participants were quite accurate in classifying access roads based on the ERC road markings (82%–89% accuracy), but somewhat less accurate for distributor and through roads (52%–69% accuracy).

Other sorts of road markings, sometimes called perceptual countermeasures, have been used over the years to produce changes in drivers' speeds at specific locations (Denton, 1980; Fildes and Jarvis, 1994; Godley et al., 1999). Most of these markings, such as dragon's teeth, herring bones, and transverse rumble lines, have been designed and employed to produce speed reductions in advance of hazardous

intersections or curves, functioning as an alert to catch drivers' attention (Agent, 1980; Charlton, 2007a; Elliot et al., 2003). Other perceptual countermeasures can result in lower speeds by virtue of their effect on drivers' perception of how fast they are traveling (Herrstedt, 2006; Martindale and Ulrich, 2010; Montella et al., 2011; van der Horst and Hoekstra, 1994). For example, one proposal to manage speeds on rural roads is to progressively reduce the spacing of dashed centre and edge lines as speed limits decrease so that lower speed roads have a higher "flicker rate" (and provide an inflated sense of speed) (Herrstedt, 2006). This proposal is related to an underlying approach called self-explaining roads which encourages the use of road markings and other road features that enable drivers to readily discriminate different road types, and possess perceptual properties that afford appropriate speed choices (Charlton et al., 2010; Theewes and Godthelp, 1992).

As can be inferred from the above brief review, the use of road markings to influence drivers' speeds have been explored in two distinct, but complementary, ways. First, road markings have been used to attract drivers' conscious attention and provide an alerting function or convey information about rules or hazards. Examples of this include warnings related to vertical or horizontal curves, also referred to as attentional processing (Ariën et al., 2017; Charlton, 2007a; Montella et al., 2015). A second function of road markings is to affect drivers' perception of speed or lane width at an implicit or unconscious level, referred to as perceptual processing (Charlton and Starkey, 2017a; Lewis Evans and Charlton, 2006; Liu et al., 2016; Montella et al., 2011). In practical terms, however, these two effects of road markings are often interrelated and inseparable.

The focus of the present research was to test different configurations of road markings to indicate speed limits on rural New Zealand roads. Conveying speed limit information through road markings could potentially increase compliance with speed limits and result in greater speed homogeneity by making speed cues continuously available and reducing uncertainty for drivers. The use of road markings could also offer a potential advantage for distracted drivers by affecting their implicit or unconscious speed control. Elsewhere we have shown that drivers are quick to detect and react to changes in road markings, even when not explicitly attending to the driving task (Charlton, 2007b; Charlton and Starkey, 2013).

Specifically, the present research: (1) compared two sets of road markings conveying speed limit information to the standard sign-only approach; (2) compared the effectiveness of explicitly informing drivers of the meaning of the markings to an implicit no-instruction condition; (3) investigated whether the effectiveness changed under conditions of high cognitive workload; and (4) assessed driver satisfaction with the use of road markings to indicate speed limits.

2. Method

2.1. Participants

One hundred and seventeen individuals with a full New Zealand driver's license were recruited for the study via notices placed on community and university webpages and through direct email invitations to participants from previous simulator studies. Fifteen drivers withdrew from the study (due to eyestrain, dizziness or other discomfort) or failed to return for the second session leaving a sample of 102 participants completing the study (55 females). The average age of these participants was 34.07 years ($SD = 13.23$, range 18–64 years). The participants reported holding a driver's license for an average of 16.57 years ($SD = 14.11$, range 1–49 years). The participants reported driving on average 163.45 km per week ($SD = 195.95$). Fifty-one of the participants reported being involved in a crash at some point during their driving history. Ethical approval for the recruitment and test protocols was received from the local research ethics review board. Participants received a \$20 gift voucher for each of the sessions they attended.

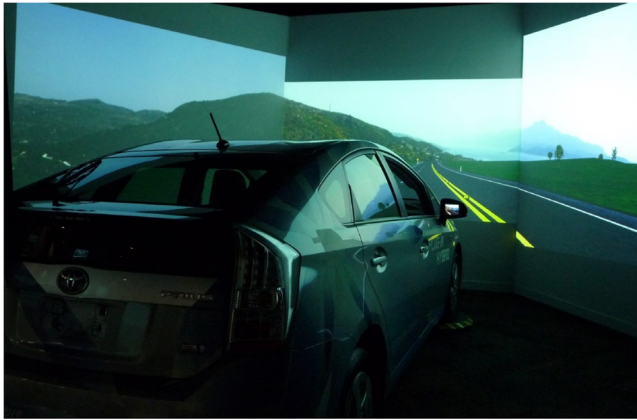


Fig. 1. The Transport Research Group driving simulator.

2.2. Simulation apparatus

The participants were seated in the Transport Research Group driving simulator consisting of a complete automobile (2010 Toyota Prius plug-in) positioned in front of three angled projection surfaces (see Fig. 1). The centre projection surface was located 2.32 m in front of the driver’s eye position with two peripheral surfaces connected to the central surface at 52° angles. The three projection surfaces were angled back away from the driver at 4.3 degrees (from the bottom to the top of the projection surface) and produced a 178.2° (horizontal) by 33.7° (vertical) forward view of the simulated roadway from the driver’s position. The image projected on the central surface measured 2.60 m wide by 1.47 m high (at a resolution of 1920 by 1200 pixels) and each of the two peripheral images measured approximately 2.88 m by 2.15 m (at resolutions of 1024 by 768 pixels). In addition, two colour LCDs with an active area of 12.07 cm by 7.49 cm each at a resolution of 640 by 480 pixels were mounted at the centre rear-view mirror and driver’s wing mirror positions to provide views looking behind the driver’s vehicle. Cameras were mounted behind the passenger seat and on the dashboard of the vehicle to record other aspects of the participants’ behaviour during the experimental sessions. The projected images and vehicle model were updated at a minimum rate of 60 frames per second. Four speakers located inside the car and a sub-woofer in the

rear cargo area presented realistic engine and road noises as appropriate. The simulation software recorded the participant’s speed, lane position and control actions automatically throughout the simulation scenario via the vehicle CAN bus. Unobtrusive cameras were mounted between the passenger and driver’s seats and on the rear-view mirror of the vehicle to monitor and record the participants’ behaviour during the experimental sessions.

2.3. Simulation scenarios

Five simulated roads were developed for the present study. Each road was 10 km long and contained a combination of straights, gentle vertical and horizontal curves based on surveyed 3-dimensional road geometry of New Zealand highways. Each of the 10 km trials contained between 9 and 13 oncoming vehicles of various types. No heading vehicles were included in the simulation scenarios. Each trial began and ended with 500 m of road posted with an 80 km/h speed limit. The remaining 9 km of each road was comprised of three different speed zones (60, 80, and 100 km/h, 3 km each) presented in different orders across the five roads.

During the first session of the experiment one of these roads was presented in each of five trials (following a three km practice road to familiarise the participants with the simulated vehicle). The purpose of the first session was to give participants experience with the road markings in the presence of the standard speed limit signs. A second experimental session occurred an average of three days after the first session (range = 1–7, $M = 3.43$, $SD = 2.24$). There was no significant difference between the four groups’ interval between the two sessions [$F(3,76) = 0.184$, $p = .907$, $\eta_p^2 = 0.007$]. During the second session the participants drove the 3 km practice road again as a refresher followed by five 10 km trials, each beginning and ending with 500 m posted with an 80 km/h speed limit. As shown in Fig. 2, in Session 2, the first two trials used Roads 1 and 3 from Session 1 and amounted to extended practice with the road markings. On Trial 3 (Generalisation) participants drove a road that was geometrically the same as Road 5 of Session 1, but had a very different appearance due to the introduction of novel scenery and a different ordering of the 60, 80, and 100 km/h speed limits (see Figs. 2 and 4). The purpose of the Generalisation trial was to examine how well the participants’ speeds learned with the road markings on one set of similar roads transferred or generalised to roads the participants had not seen before. On Trial 4 (Workload) the

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
Session1	Practice 3 km	Road 1 10 km	Road 2 10 km	Road 3 10 km	Road 4 10 km	Road 5 10 km
Session2	Practice 3 km	Road 1 10 km	Road 3 10 km	Generalis. Road 5 ^x	Workload Road 2 ^y	No Signs Road 2 ^z
Control (only 1 session)	Practice 3 km	Road 1 10 km	Road 4 10 km	Road 5 10 km	Generalis. Road 5 ^x	Workload Road 2 ^y

x = Road 5 with different scenery

y = Road 2 with different speed zone order

z = Road 2^y with different scenery

Fig. 2. The order of simulated roads presented to the participants.

participants were presented with Road 2 (with a different order of speed zones to Session 1), and a secondary task (Paced Auditory Serial Addition Task; PASAT) which presented an audio recording of a series of digits (from 1 to 9), one presented every 3 s with the requirement that participants were to say out loud the sum of the last two digits they heard. The fifth and final trial (No Signs) was intended to determine whether the road markings alone were sufficient to maintain speed compliance after the participants' experience with them. During this trial participants were presented with Road 2 (with yet another order of speed zones) which had been made visually distinct with a new and novel background scenery. During this trial all of the speed limit signs were removed, but the road markings associated with each speed zone remained as before. The participants were also asked to perform a verbal detection task (naming what attracted their attention during the drive) to see if they noticed the changes in road markings, as described later in the Procedure. Participants in the Control Group attended a single experimental session composed of Road 1, Road 4, Road 5, Generalisation Road, and the Workload Road.

2.4. Road markings

Two sets of road markings were used in the experiment; participants experienced either one or the other depending on which experimental group they were assigned to (described below in the Procedure). For each of the two sets of markings, different configurations of centre and edge lines were associated with 60, 80, and 100 km/h speed zones. Road markings were always paired with the corresponding speed signs with the exception of the final road on Session 2 (No Signs Trial). The markings associated with 80 km/h in both sets were configured according to "standard" road marking guidelines (Manual of traffic signs

and markings; MOTSAM, 2010), as were all of the roads and speed zones in the Control group's single session. As shown in Fig. 3, this standard configuration consisted of a dashed white centre line (3.0 m dashes with 7.0 m spaces), and solid white edge lines, with 3.5 m lanes measured from the centre of the road to the centre of the edge line (all white lines were 0.1 m wide). In addition there was a paved shoulder 1.5 m wide to the outside of the edge line. This configuration is standard for two-lane rural roads in New Zealand regardless of speed limit. The first set of experimental markings, referred to as Attentional, were designed so that the markings associated with speeds slower or faster than this 80 km/h standard would be visually and explicitly distinct to drivers. These attentional road markings were based on the ERC markings used in previous research (Aarts and Davidse, 2008; Stelling-Konczak et al., 2011). In 60 km/h zones the edge line was changed from a solid white to a dashed white (to match the centre line). For 100 km/h zones the centre line was changed to a 0.3 m green line, edged on either side with 0.1 m dashed lines. In order to maintain the same 3.5 m lane width as the other speeds, the paved road was widened so that the distance from the centre of the road to the centre of the edge line was 3.7 m.

The second set of road markings, called perceptual markings, was similar to the attentional markings but also manipulated the width and spacing of the line markings to influence the drivers' perception of speed (after Herrstedt, 2006). At 80 km/h the markings and lane width were the standard values, but at 60 km/h the lane width was decreased to 3.0 m and the paved verge was reduced to 0.5 m. As with the Attentional set, the 60 km/h edge lines were changed from solid to dashed, but they also were reduced in length, with 2.4 m dash length and a 5.6 m spacing between dashes. If driven at the posted speed, the frequency of dashes (2.2 dashes per sec) matched the frequency of

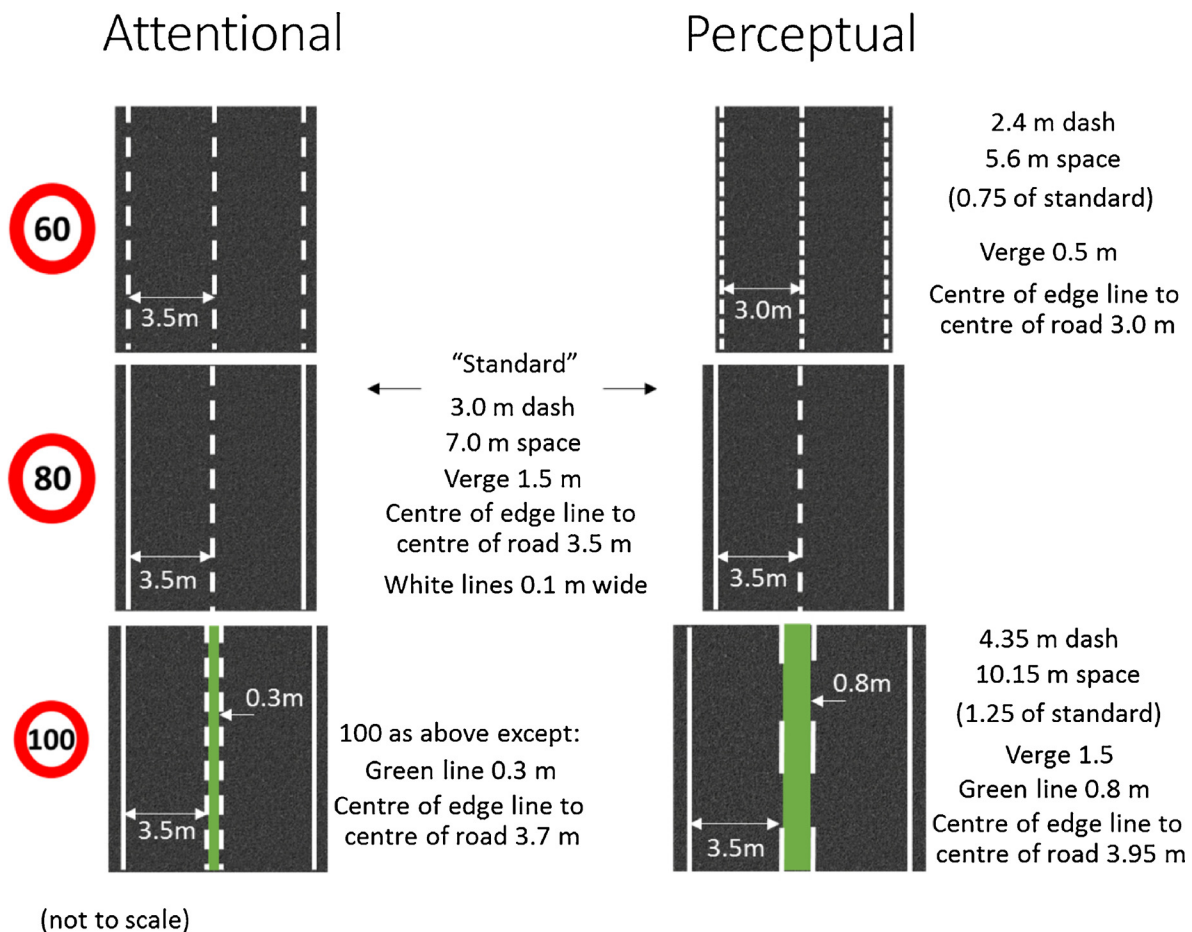


Fig. 3. The road marking configurations in the Attentional and Perceptual sets.



Fig. 4. The road markings and background scenery from a driver's point of view. Top: the default background (used for Session 1 trials, and trials 1, 2, & Workload Trial of Session 2) and an example of an 80–60 km/h speed transition with perceptual markings. Middle: background scenery used during Generalisation Trial, and a 60–100 km/h speed transition with perceptual markings. Bottom: background scenery during the No Signs Trial and an 80–60 km/h transition with attentional markings.

dashes of the standard markings at 80 km/h. For the 100 km/h markings, the dashes were increased to 4.35 m in length and spacings to 10.1 m; again matching the standard rate of dashes when driving at 100 km/h. In addition, a 0.8 m wide green centre line was added, and the road was widened to maintain a continuous lane of 3.5 m (3.95 m from centre of road to centre of edge line). These two sets of lane markings were defined in consultation with the national road controlling authority, and in those consultations the decision was made to base the 80 km/h configuration tested on the current New Zealand standard for two-lane rural road markings (as 80 km/h was identified as best practice safe speeds for these rural roads). Fig. 4 shows how the markings appeared from the drivers' point of view.

2.5. Questionnaire booklet

At the end of each experimental session the participants answered several questions in a questionnaire booklet. Following Session 1,

participants completed questions about demographics (e.g., age, gender), and driving history (driving experience, crashes). Following Session 2, participants were shown photos of the three road marking configurations they had seen during the experiment and asked what the correct speed limit was for each road (participants in the Control group were not asked this question, because the roads they drove contained standard road markings). A final question asked participants to rate the acceptability of using road markings to indicate speed limits ('1'; not at all acceptable and useful to '10' very acceptable and useful).

2.6. Procedure

Upon arrival at the laboratory the participants provided written informed consent and were then assigned to one of four experimental groups or a Control group. Twenty participants were randomly assigned to each of the Attentional-Explicit, Attentional-Implicit, Perceptual-Explicit, and Perceptual-Implicit groups (a total of 80) and another 22 participants completed the experiment in the Control group. Participants in the two Explicit groups were shown photos of the road marking configurations appropriate to their group (either Attentional or Perceptual) and given verbal descriptions of how the road markings corresponded with the three posted speed limits (60, 80 and 100 km/h). Participants in the two Implicit groups and the Control group were not given instructions regarding the road markings or speed limits. All participants were then seated in the driving simulator car and drove the 3 km practice road to familiarise themselves with the simulator while the experimenter gave advice and instruction regarding the simulator and the experimental setup. The participants were given the opportunity to repeat the practice road if they so desired. The participants were then given the five simulated roads with the instruction to "choose the same speed as you would in your own car and follow the road rules." Each of the five simulated drives was separated by a 2–3 min break between each drive. At the end of the first session the participants completed the first part of the questionnaire booklet (demographic and driving history questions) as described earlier and participants in the four experimental groups were scheduled with a time to attend their second session within the next few days. All participants were then thanked and compensated for their participation with a \$20 gift voucher.

When the participants in the experimental groups returned for their second session they began by repeating the 3 km practice drive as a warm-up. The participants then drove the five roads as shown in Fig. 2, each separated by a 2–3 min break. The first two trials in the series were roads that they had previously driven in Session 1 and were included primarily to see whether any changes in their speed control acquired during the course of Session 1 had been retained (particularly for the Implicit groups). The third trial (fourth trial for Control group participants) was geometrically identical to road 5 from Session 1, but was made visually distinct by changing the scenery to see if speed control acquired during the experiment generalised to what appeared to be a new road. (When we have used this manipulation previously participants have not recognised the road as being the same and their speed and steering control returned to inexperienced or baseline levels of performance; Charlton and Starkey, 2013). For the fourth trial (fifth trial for Control group), the participants were asked to engage in the secondary PASAT task while driving, having been instructed on how to do the serial addition task during the break before they began driving the road, including a one-minute audio-only practice string of digits. Then participants drove a final road in which speed limit signs were removed but the road markings associated with the different speed zones remained (participants in the Control group did not experience this trial). While they drove this road the participants were asked to perform a verbal detection task as follows: "tell us whatever catches your attention as you drive. To do this we want you to flash your headlights and then say out loud whatever caught your attention. Make sure to say it clearly so I can hear you. This isn't a test to see how much you can find, we just want to know what catches your attention as you drive, things that are

interesting or changing in the road or road environment". Upon completion of the last road, the participants completed the second half of the questionnaire booklet and were thanked for their participation with a \$20 gift voucher.

2.7. Data analysis

Inasmuch as the purpose of the Session 1 trials were to provide extended experience with the road markings, analysis of the results focussed on the Session 2 data only. Arguably the findings of greatest interest were three Session 2 trials in particular; when the markings were applied to roads the participants had not seen previously (Generalisation Trial); when participants experienced increased cognitive load (Workload Trial); and when speed signs were removed and participants had to rely on only the road markings (No Signs Trial). For each of these trials, the participants' speeds were averaged across 100 m sections of each of the three speed limit zones (60, 80, & 100 km/h) for each of the roads. These sections were chosen so that they occurred in the last quarter of the speed zone and did not contain any significant horizontal or vertical curves that would affect the participants' speeds, to remove any influence of road geometry on the comparisons. For each of these three trials the mean speeds for each group at each speed limit were compared with a 3 (Speed limit: 60, 80 or 100 km/h) \times 5 (Group: Attentional-Explicit, Attentional-Implicit, Perceptual-Explicit, Perceptual-Implicit, Control) mixed-design Anova. When violations of the sphericity assumption for the repeated measures/mixed design Anovas were detected, the significance tests were corrected according to the Greenhouse-Geisser formula. Post hoc comparisons between the five groups were made using Dunnett's *t* comparisons or Bonferroni corrections as appropriate.

In addition, we examined the transitions between speed zones during the No Signs Trial (Session 2) by taking the mean speeds in the last quarter of each speed limit zone calculated as above, and every 10 m during the transition from the 80 km/h to the 60 km/h markings. A measure of speed reduction was calculated at three points at the transition by subtracting each participant's mean speed at 30 m, 100 m, and 200 m after the speed limit change from their speed 100 m prior to the change. A 2 (Markings: Attentional or Perceptual) \times 2 (Instruction: Explicit or Implicit) Anova was calculated for the speed change at each of the three post-transition distances. Finally, the participants' ratings of the acceptability of using road markings to indicate speed limit were compared using a Kruskal-Wallis independent samples test.

3. Results

3.1. Generalisation trial

Fig. 5 shows the participants' mean speeds for the Generalisation Trial, when the road markings and signs the participants had practiced with during Session 1 and the first two trials of Session 2 were applied to a road that the participants had not encountered previously (geometrically this simulated road was the same as Road 5 from Session 1 but made to look different by virtue of different scenery as shown in Fig. 4). As can be seen in the figure, the participants showed good speed differentiation (chose different speeds for the different speed limits). The 3 \times 5 mixed-design Anova showed a significant effect of speed limit on participants' mean speeds [$F(2,194) = 4260.61, p < .001, \eta_p^2 = 0.978$]. The Anova also showed a small but reliable overall difference between the five groups' mean speeds [$F(4,97) = 3.56, p = .009, \eta_p^2 = 0.128$], but no group by speed limit interaction [$F(8,194) = 1.78, p = .084, \eta_p^2 = 0.068$].

As shown in Fig. 5, compliance with the 60 and 100 km/h speed limits was good, but the participants in each group exceeded the 80 km/h speed limit. It should be remembered that the road markings under this speed limit were identical for all five groups (and the "standard" road marking for rural roads in New Zealand regardless of speed limit).

Generalisation

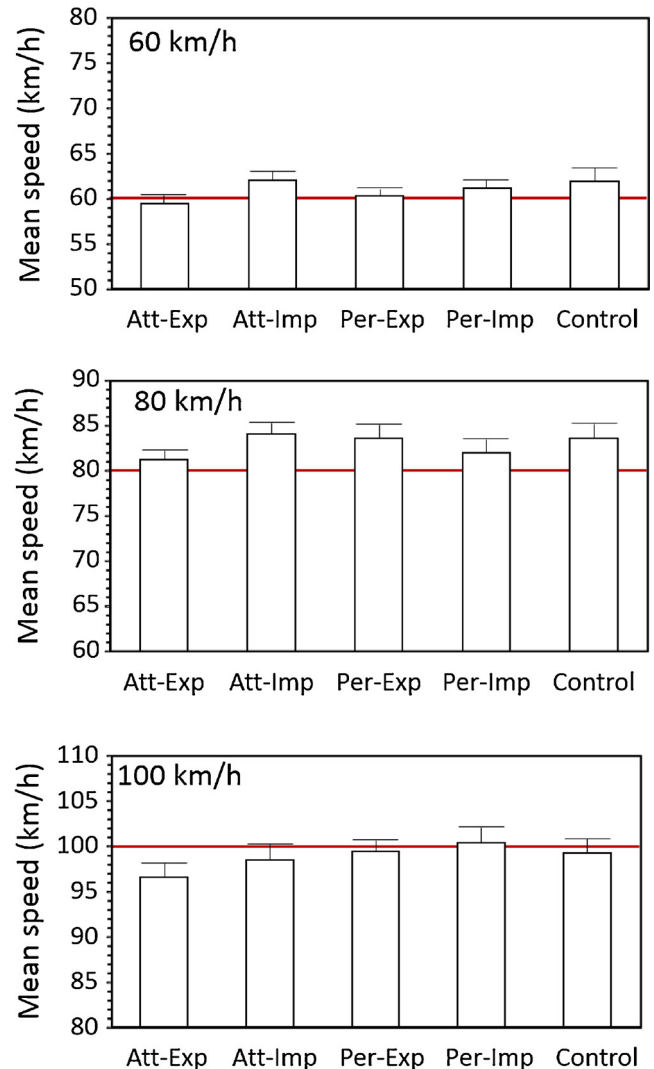


Fig. 5. Participants' average speeds at each of the three speed limits during the Generalisation Trial. Error bars indicate the 95% confidence intervals.

When mean speeds for the Generalisation Trial were averaged across the three speed limits for each participant the Control group participants displayed the highest speeds ($M = 81.57$ km/h, $SD = 2.69$) followed closely by the Attentional-Implicit group ($M = 81.52$ km/h, $SD = 2.12$). Post hoc comparison of the four experimental groups to the Control group's speeds using Dunnett's adjustment showed that only the Attentional-Explicit group was significantly lower than the Control group (by an overall average of 2.51 km/h, $p = .005$).

3.2. Workload trial

Fig. 6 shows the participants' mean speeds for the Workload Trial, when the participants engaged in a secondary PASAT task as they drove. The simulated road was the same as Road 2 of Session 1, both geometrically and visually, albeit the speed limit zones were in a different order. As with the Generalisation Trial, the participants displayed very different speeds for the three speed limits [$F(2,194) = 1362.67, p < .001, \eta_p^2 = 0.934$]. There was not, however, any significant overall difference between the five groups [$F(4,97) = 1.73, p = .149, \eta_p^2 = 0.067$] and depended on which speed limit was in effect, as reflected in a significant group by speed limit interaction [$F(8,194) = 5.81, p < .001, \eta_p^2 = 0.193$].

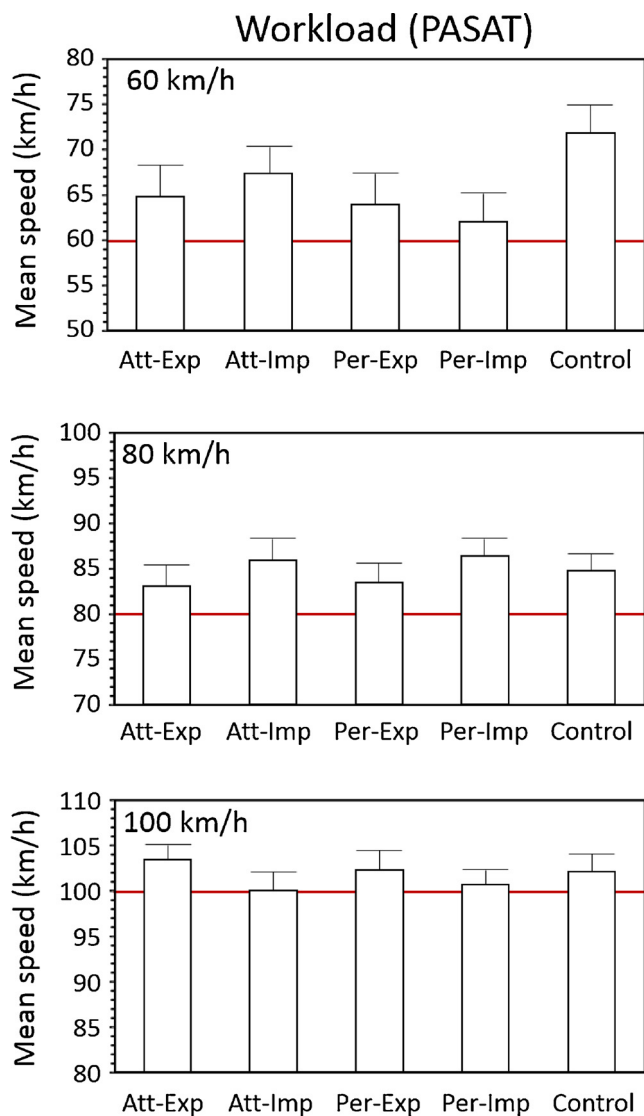


Fig. 6. Participants’ average speeds at each of the three speed limits during the Workload (PASAT) Trial. Error bars indicate the 95% confidence intervals.

The significant interaction resulted from significant group differences during the 60 km/h speed zone where the Control group displayed the highest mean speeds of any group ($M = 71.79$ km/h, $SD = 11.69$). Dunnett’s adjusted comparisons indicated that this was significantly higher than the Attentional Explicit group ($M = 64.72$, $SD = 7.04$, $p = .014$), the Perceptual-Explicit group ($M = 63.85$, $SD = 5.07$, $p = .005$), and the Perceptual-Implicit group ($M = 61.95$, $SD = 5.17$, $p > .001$). The Attentional-Implicit group’s mean speed was lower than the Control group ($M = 67.35$, $SD = 7.14$) but not reliably ($p = .200$). There were no group differences at the 80 km/h speed zone (as you would expect because the road markings for all five groups were identical); nor were there any identified for the 100 km/h speed limit.

The most striking effect of the secondary task, however, was the degree of non-compliance with the speed limits, particularly at 60 km/h and 80 km/h, as shown in the figure. As mentioned above, at 60 km/h compliance with the speed limit was poorest for participants in the Control group (an average of nearly 12 km/h over the speed limit), followed by the Attentional-Implicit group (approximately 7 km/h over). During the 80 km/h sections, the participants’ mean speeds were also over the speed limit, but only by an overall average of 2.89 km/h (Bonferroni corrected comparisons did not reveal significant differences

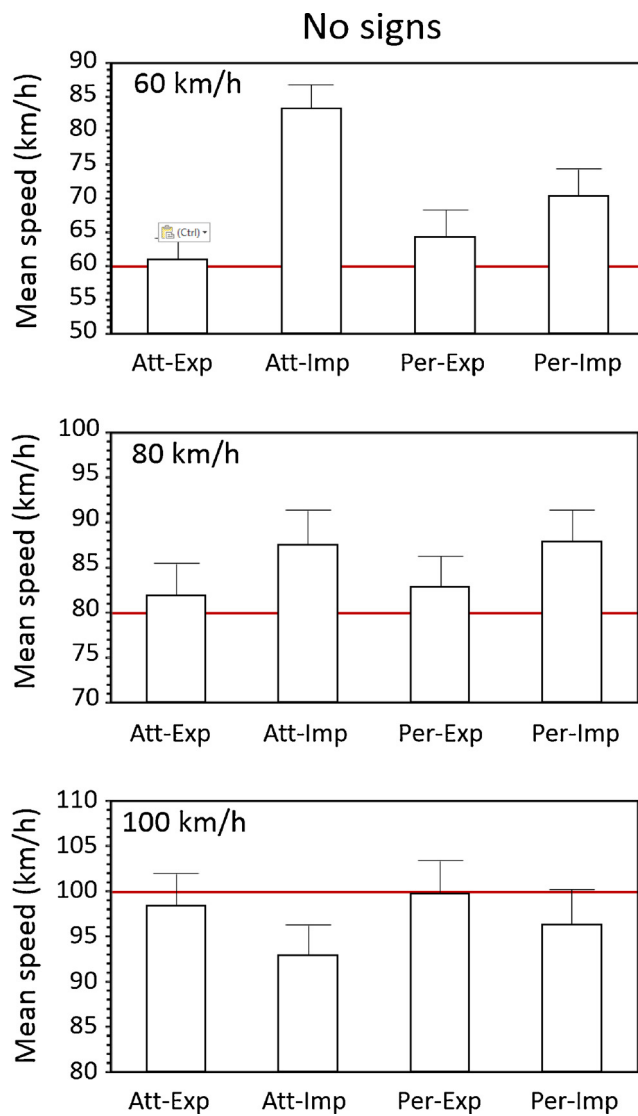


Fig. 7. Participants’ average speeds at each of the three speed limits during the No Signs Trial. Error bars indicate the 95% confidence intervals.

between any of the groups). During the 100 km/h section, the participants’ mean speed was at the speed limit ($M = 101.69$ km/h, $SD = 4.81$), and there were no statistically reliable differences between any of the groups.

3.3. No signs trial

For the last trial of Session 2 all speed limit signs were removed and participants had to rely only on the road markings (participants in the Control group did not experience this condition). The average speeds from this trial are shown in Fig. 7 and as can be seen, many of the participants were able to differentiate their speeds in accordance with the speed limit markings. This was reflected in a reliable difference in mean speeds across the three speed limits [$F(2,152) = 311.25$, $p < .001$, $\eta_p^2 = 0.804$], but there was also a significant difference between the groups [$F(3,76) = 4.57$, $p = .005$, $\eta_p^2 = 0.153$] and a large group by speed limit interaction [$F(6,152) = 17.87$, $p < .001$, $\eta_p^2 = .414$].

At the 60 km/h speed limit, the two Implicit groups were clearly faster than the two Explicit instruction groups. A 2×2 Anova comparing the two types of instruction (Explicit or Implicit) and the two road marking types (Attentional or Perceptual) revealed a large

instruction effect [$F(1,76) = 51.28, p < .001, \eta_p^2 = 0.403$], a reliable marking effect [$F(1,76) = 5.96, p = .017, \eta_p^2 = 0.073$], and a reliable marking by instruction interaction [$F(1,76) = 51.28, p < .001, \eta_p^2 = 0.403$]. Examining the pairwise comparisons between the groups (Bonferroni corrected), the Attentional-Implicit group had by far the highest speeds, an average of 23.35 km/h over the speed limit, significantly higher than the other three groups ($ps < .001$). The Perceptual-Implicit group's speeds (10.29 km/h over the speed limit) were higher than the Attentional-Explicit group ($p = .008$) but were not different to the Perceptual-Explicit group ($p = .214$), and speeds for the two Explicit groups were not reliably different to one another.

At the 80 km/h speed limit there was a significant effect of instruction [$F(1,76) = 7.53, p = .008, \eta_p^2 = 0.090$] such that the Explicit groups drove an average of 5.38 km/h slower than the Implicit groups, but there was no reliable difference between the two types of marking [$F(1,76) = 0.111, p = .739, \eta_p^2 = 0.001$] or interaction between Instruction and Marking [$F(1,76) = 0.016, p = .899, \eta_p^2 = 0.001$]. Similarly, for the 100 km/h speed limit there was a significant difference for Instruction [$F(1,76) = 5.17, p = .026, \eta_p^2 = 0.064$] with the Implicit groups driving an average 4.51 km/h slower than the Explicit groups and 5.45 km/h slower than the speed limit. There were no detectable differences due to type of marking [$F(1,76) = 1.477, p = .228, \eta_p^2 = 0.019$] or instruction by marking interaction [$F(1,76) = .271, p = .604, \eta_p^2 = 0.004$].

3.4. Speed transition

Fig. 8 shows the change in speeds at the point of the 80 to 60 km/h speed transition during the No Signs Trial. As shown, the mean speeds for the Perceptual-Explicit group showed an immediate drop in speed, a speed reduction of 10.06 km/h at 30 m past the speed limit change (as calculated by subtracting each participant's speed from their speed 100 m prior to the speed limit change). The mean speeds for the Attentional-Explicit group also dropped, an average reduction of 6.53 km/h, followed by the Perceptual-Implicit group (mean speed reduction = 3.01 km/h) and the Attentional-Implicit group (mean speed reduction = 0.71 km/h). A 2×2 Anova comparing the speed reductions associated with the two road marking types (Attentional or Perceptual) and the two types of instruction (Explicit or Implicit) indicated a significant effect of instruction [$F(1,76) = 12.75, p = .001, \eta_p^2 = 0.144$], but no effect of type of marking [$F(1,76) = 2.62, p = .110, \eta_p^2 = 0.033$] or interaction between instruction and marking [$F(1,76) = 0.117, p = .734, \eta_p^2 = 0.002$]. Post hoc pairwise comparisons (Bonferroni-adjusted) showed that the Perceptual-Explicit group showed the largest speed reduction, significantly more than either the

Attentional-Implicit group ($p = .003$) or Perceptual-Implicit group ($p = .043$) whereas none of the other pairwise comparisons were reliably different ($ps > .05$).

By 100 m after the speed limit sign the Attentional-Explicit group had decreased their speeds even more ($M = 12.10$ km/h), by nearly the same amount as the speed reduction shown by the Perceptual-Explicit group ($M = 13.05$ km/h), although neither of them had fully reached the 60 km/h speed limit ($M = 67.05$ km/h, $SD = 7.62$; and $M = 68.56$ km/h, $SD = 12.25$ respectively). The Perceptual-Implicit group had also continued to reduce their speeds, by 5.27 km/h at the 100 m point. A 2×2 Anova on the speed reductions at 100 m after the transition once again showed a significant effect of instruction [$F(1,76) = 26.17, p > .001, \eta_p^2 = 0.256$], but no effect of type of marking [$F(1,76) = 1.77, p = .188, \eta_p^2 = 0.023$] or interaction between instruction and marking [$F(1,76) = 0.642, p = .426, \eta_p^2 = 0.008$]. Pairwise comparisons showed that the two explicit groups were significantly different from the two implicit groups ($ps < .05$) but were not different from one another.

At the 200 m point, the Attentional-Explicit group had reduced their speeds to an average of 63.04 km/h ($SD = 6.31$), slower than the Perceptual-Explicit group at 69.33 km/h ($SD = 7.38$), while the Perceptual-Implicit group had only reduced their speeds to 78.70 km/h ($SD = 13.47$). The 2×2 Anova on the mean speed reductions showed a significant instruction effect [$F(1,76) = 49.33, p > .001, \eta_p^2 = 0.394$] and a significant interaction of instruction by marking [$F(1,76) = 10.85, p = .002, \eta_p^2 = 0.125$], but no main effect of marking [$F(1,76) = 0.335, p = .564, \eta_p^2 = 0.004$]. Bonferroni corrected pairwise comparisons confirmed that the Attentional-Implicit group showed the least reduction in speed by 200 m after the transition; their speed change was significantly less than any of the other groups ($ps < .05$). The Attentional-Explicit group showed the greatest reduction in speed at 200 m after the transition, but was not reliably more than that shown by the Perceptual-Explicit mean ($p = .351$).

3.5. Comprehension and acceptability ratings

At the end of Session 2 the participants were shown photos of the three road markings they had seen during their simulated drives and asked to write down the speeds associated with each of them. The percent of participants in each group providing correct speeds for all three markings is shown in Fig. 9. All of the participants in the two Explicit groups gave correct answers for each of the road markings. Only 35% of participants in the Attentional-Implicit group were able to identify the correct speeds for the markings, and 60% of the Perceptual-Implicit participants successfully identified the correct speeds. Finally, the median acceptability rating for using road markings to indicate the speed limit was 9 (where 10 = "very acceptable and useful"). A Kruskal-Wallis independent samples test failed to detect any differences between the groups in their ratings of acceptability [$H = 7.56, p = .109$].

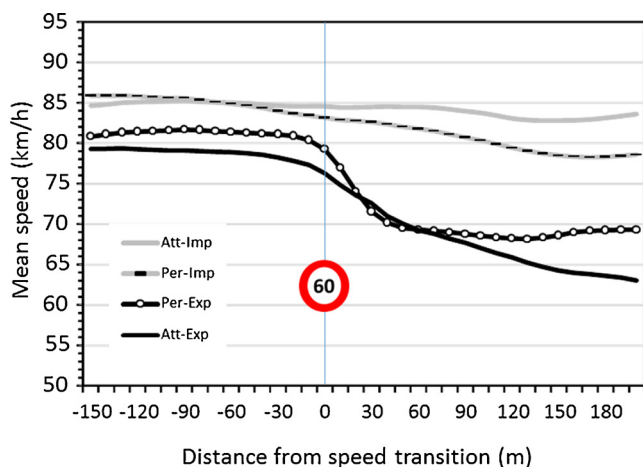


Fig. 8. Mean speeds at the 80–60 km/h speed change transition point on the no-signs road.

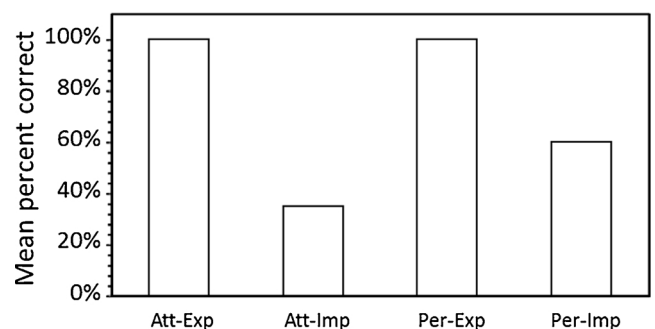


Fig. 9. The percent of participants who accurately identified the correct speeds for each of the road markings at the end of Session 2.

4. Discussion

At the outset of this research we asked whether the use of road markings to indicate speed limits would improve driver compliance with the limits. Based on the findings of the present study we can say the answer appears to be a qualified yes. Once the drivers were familiar with the markings all of the marking and road sign combinations were associated with good speed differentiation and speed limit compliance, even when applied to a driving environment the participants had never experienced before. The road markings delivered better compliance with the speed limits in the 60 and 100 km/h zones, and poorer compliance in the 80 km/h zone. This is perhaps understandable because the markings for all of the groups in this zone were the same as the current rural road standard markings in New Zealand (regardless of speed limit). Across all three speed limits, the best compliance relative to the Control group was observed for the participants in the Attentional-Explicit group. In the 60 and 100 km/h speed environments, they were followed closely by the participants in the Perceptual-Explicit group.

Unlike the findings reported by Daniels et al. (2010), increased mental load during the Workload (PASAT) trial did not result in an overall reduction in speed. Instead, participants' speeds were generally higher, and compliance poorer, but the additional road markings remained effective at assisting participants in the two Perceptual groups and the Attentional-Explicit group to keep their speeds low in the 60 km/h limit. The Attentional-Implicit participants, however, were not reliably better than the Control group participants under these conditions. The reason for the difference between the present study and the Daniels et al. (2010) study is not clear, but may be due to slightly different instructions given to the participants. Daniels, Vanrie, Dreesen and Brijs instructed their participants to “drive as close as possible to the indicated speed limit but otherwise to drive as they would normally do” (p. 956), whereas participants in the present study were simply instructed to “Remember to choose the same speed as you would in your own car and follow the road rules”.

When the speed limit signs were removed and participants had to rely solely on the road markings it became clear that there was a significant advantage associated with the Explicit instruction conditions. The participants who had received explicit instructions about the meaning of the markings drove closer to the speed limit at 60 and 100 km/h, whereas the implicit groups appeared to adopt a strategy of driving somewhere between 85–90 km/h for all of the roads. It is not clear to what degree the participants attended to the road markings while driving. During the No Signs Trial the participants were asked to comment when things in the driving situation caught their attention. Most of the items noted by the participants were oncoming vehicles, intersections, and roadside scenery and terrain; only rarely were road markings mentioned by the participants. When the comprehension data are considered, it is easy to see that simple exposure to the markings conferred little or no significant understanding of the markings' meanings to the participants in the Implicit groups, in spite of having driven in the presence of the experimental marking schemes for nearly 90 km. Having said that, there was still a small additional advantage to the Perceptual configuration for the 60 km/h speed limit, as evidenced by the lower mean speeds displayed by the Perceptual-Implicit group. This effect could also be seen in the speed change at the transition from 80 to 60 km/h. Relative to the Attentional-Implicit group, which showed little or no change in speed at the transition, the Perceptual-Implicit group showed gradual but significant slowing and by 100 m had reduced speeds by an average of more than 5 km/h. Whether this was due to the changed spacing in the dashed lines or due to the reduced lane width is not possible to tell from these data.

The combination of explicit instruction and perceptual markings produced an immediate and rapid deceleration at the transition, but by 200 m the amount of speed reduction was no different to the Explicit-Attentional group, and when measured in the last quarter of this speed

zone (over 2 km later), there was no difference between the two types of markings, nor was there at any of the 80 and 100 km/h limits. Both explicit groups showed superior speed differentiation compared to the Implicit groups, and interestingly, during the 100 km/h speed zone, the effect was to keep speeds closer to 100 km/h, a higher speed than driven by the Implicit groups, particularly the Attentional-Implicit group.

As with any laboratory study, readers of this work should ask about the degree to which the behaviour displayed by our research participants in the simulator will be representative of other drivers' performance, in their own cars, on other roads. In answer, we feel reasonably confident that the findings of this study will generalise widely to other drivers and situations. The simulated roads were created using road survey data to reflect the actual dimensions and geometry of several New Zealand state highways, the same as a large number of similar studies we have conducted in the past (e.g., Charlton, 2007a, 2009; Charlton and Starkey, 2013). When we have conducted on-road trials alongside laboratory-based trials, speeds on the same roads have not differed by more than a few km/h (e.g., Charlton and Starkey, 2016; Charlton et al., 2014). Even more importantly, however, with increasing use of driving simulators for research it has become apparent that the pattern of effects obtained with simulators (of the sort used in the present study) will be the same as the pattern of effects seen on the road, provided the conditions or treatments being compared are tested in equivalent fashion (good internal validity). In other words, with good internal validity in testing, relative validity with regard to the direction and relative size of the effects is obtained, and is in fact more important for ensuring generalisability of results than the exact correspondence between speeds obtained in simulation and on the road (Bella, 2008; Godley et al., 2002; Kaptein et al., 1996; Törnros, 1998).

The findings suggest there would be value in providing additional road markings of the sort tested in this study. We suggest that providing continuous speed limit information to drivers would improve safety by increasing the homogeneity of driving speeds on the roads (Aarts and van Schagen, 2006; van Nes et al., 2010) as well as assist the formation of correct expectations and speed choices at an implicit, automatic level (Charlton and Starkey, 2017a,b). Both sets of markings tested were effective compared to the control group, and it is possible that other configurations would be equally effective. Whether the markings would continue to be effective over the long term is also unknown, although across the two sessions in the present study the markings became more effective rather than less. Further research could productively examine the time course of drivers' adaptation to the markings either in the laboratory or in a field trial.

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