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Overt vs. covert speed cameras in combination with delayed vs. immediate feedback to the offender

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ABSTRACT

Speeding is a major problem in road safety because it increases both the probability of accidents and the severity of injuries if an accident occurs. Speed cameras are one of the most common speed enforcement tools. Most of the speed cameras around the world are overt, but there is evidence that this can cause a "kangaroo effect" in driving patterns. One suggested alternative to prevent this kangaroo effect is the use of covert cameras. Another issue relevant to the effect of enforcement countermeasures on speeding is the timing of the fine. There is general agreement on the importance of the immediacy of the punishment, however, in the context of speed limit enforcement, implementing such immediate punishment is difficult. An immediate feedback that mediates the delay between the speed violation and getting a ticket is one possible solution. This study examines combinations of concealment and the timing of the fine in operating speed cameras in order to evaluate the most effective one in terms of enforcing speed limits. Using a driving simulator, the driving performance of the following four experimental groups was tested: (1) overt cameras with delayed feedback, (2) overt cameras with immediate feedback, (3) covert cameras with delayed feedback, and (4) covert cameras with immediate feedback. Each of the 58 participants drove in the same scenario on three different days. The results showed that both median speed and speed variance were higher with overt than with covert cameras. Moreover, implementing a covert camera system along with immediate feedback was more conducive to drivers maintaining steady speeds at the permitted levels from the very beginning. Finally, both 'overt cameras' groups exhibit a kangaroo effect throughout the entire experiment. It can be concluded that an implementation strategy consisting of covert speed cameras combined with immediate feedback to the offender is potentially an optimal way to motivate drivers to maintain speeds at the speed limit.

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1. Introduction

Speeding is a major problem in road safety due to the increase it causes both in the probability of accidents and in the severity of injuries when an accident occurs (Elvik, 2009). Harsha et al. (2007) presented a general rule of thumb for the increased risk from speeding: "when travel speed increases by 1%, the injury crash rate increases by about 2%, the serious injury crash rate increases by about 3%, and the fatal crash rate increases by about 4%" (p. 3). Some researchers argue that collisions rate is more correlated with speed variance than speed level per se (e.g., Garber and Ehrhart, 2000; Lave, 1985; Quddus, 2013). However, Elvik et al., (2004) stressed that in reality there is a strong correlation between mean and variance and concluded that it might be difficult to separate the effects of mean speed and speed variance on collisions.

Police enforcement of the speed limit is one of the most effective tactics to address the dangers of speeding. Although a positive correlation between the extent of enforcement and a reduction in accident rates has not been clearly demonstrated in individual study results, this correlation has been shown when the data of those studies was aggregated in a meta-analysis (Elvik, 2011). Another enforcement tool commonly employed is to install speed cameras. Yet the evidence on the benefits of this method is still inconclusive. Some have found speed cameras to be associated with an estimated 17–25% reduction in injuries from accidents (see review in Thomas et al., 2008), or that there were resultant reductions in the number of collisions, ranging from 8% to 49% for all collisions and from 11% to 44% for fatal and serious injury collisions, in the areas where speed cameras were located (Wilson et al., 2010). Conversely, other researchers reported that they failed to find a beneficial effect on the number of collisions or injuries from speed cameras (Novoa et al., 2010; Skubic et al., 2013).

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Furthermore, Aljassar and Ali (2003) found an increase of 5% in fatal accidents after the installation of speed cameras in Kuwait. Several arguments against the use of speed cameras have been presented (Delaney et al., 2005): (1) the aim of cameras is to raise revenue for the government rather than improve road safety; (2) speed cameras are perceived as unfair because the system cannot notify the offender on the spot, which does not allow for the opportunity to explain the circumstances of the offence (as can be done with police officer); (3) the perceived reliability of speed cameras is low; and (4) speed cameras can be considered an invasion of privacy.

Speeding cameras can be either fixed cameras, which are installed in a specific location, usually a box mounted on a pillar, or they can be mobile cameras, installed in police vehicles, operated by trained policemen. These cameras can be either visible ('overt') or hidden ('covert'). Overt cameras are fixed speeding cameras, while covert cameras can be camouflaged, in their surroundings as fixed cameras or hidden mobile cameras. The added advantage of covert cameras is the increase in the uncertainty about their location. There is an ongoing debate on whether overt or covert cameras are more effective; however this effectiveness is dependent on the specific objective being targeted. Researchers have argued that overt cameras are more appropriate if the aim is to deter speeders at unsafe locations rather than to raise revenue for the government (see Delaney et al., 2005); however, other evidence has shown that covert countermeasures may reduce collision rates and average speeds more extensively than overt countermeasures (Diamantopoulou and Cameron, 2002; Keall et al., 2001). One of the shortcomings of overt cameras, unlike covert cameras, is their typical effect on drivers facing the camera, i.e., the tendency to slow down near the camera's location and to speed up after passing the camera to compensate for the loss of time. The occurrence of this effect, which Elvik (1997) named the "kangaroo effect", was shown in two different studies. Both studies found that the mean speed measured at 500 m after the location of the speed camera had increased back to match the speed measured 500 m before this location (Keenan, 2002; Nilsson, 1992 in Elliott and Broughton, 2005). Moreover, Keenan (2002) reported that 500 m after the camera's location, about 80% of the drivers were exceeding the speed limit. Consequences of such a kangaroo effect may include increased chances of a rear-end collisions if the camera is noticed by the driver at the last moment, and he or she decelerates abruptly. The trade-offs in risks and benefits of overt speed cameras are not necessarily clearly defined. In fact, Shin et al. (2009) reported an increase of rear-end collisions after the implementation of a speed camera program. A similar pattern was observed for red light cameras which were found to increase low-severity rear-end crashes (e.g., Erke, 2009; Goodwin et al., 2013; Høye, 2013). Assuming that red light cameras actually prevent many fatal injuries, this increase in the rear-end collisions is the lesser of two evils. However, this same tradeoff may not be applicable in the case speed cameras are not located at major intersections, because the probability of a fatal collision occurring exactly at the camera's location is not as high as in an intersection. Additionally, in a critical review Thomas et al. (2008) argued that although speed camera-related collisions decrement estimated to range between 20% and 25%, there may be some shifting of collisions to other places along the road; thus, the evaluation of camera programs should take this "negative spill over" into consideration. Other researchers have made similar claims concerning the localized deterrent effect of overt speed cameras, compared to a more general deterrent effect associated with covert speed cameras (e.g., Cameron and Delaney, 2010; Keall et al., 2001, 2002).

Another issue relevant to the effectiveness of enforcement countermeasures is the timing of the penalty. In most cases, the penalty for speeding is a fine, whose amount depends on the severity of the violation in some countries (e.g., in Norway, see Elvik, 1997). When the speeding violation is very severe, however, the penalty can be the suspension of the driver's license or even a jail sentence. These penalties are usually imposed a long time after the speeding violation has occurred. When considering punishment in a broader context, most studies that have examined punishment timing agree that the effectiveness of delayed punishment is reduced compared to immediate punishment (Abramowitz and O'Leary, 1990; Banks and Vogel-Sprott, 1965; Cheyne and Walters, 1969; Penney and Lupton, 1961). Kamin (1959) proposed the concept of 'delayed punishment gradient', which was confirmed with human participants by Banks and Vogel-Sprott (1965). According to this concept, the longer the punishment is delayed, the less effective it is.

In the context of traffic laws and speed limit enforcement, the implementation of these insights is not a simple task. Speeding tickets are almost always issued a long time after the actual traffic violation happened; therefore, the driver may not even remember the incident itself. One solution which might improve the effectiveness of the delayed punishment is to develop technologies that mediate the delay between the law violation, in this case exceeding the speed limit, and the punishment, i.e., getting a speeding ticket (Meindl and Casey, 2012). This solution could be efficient since in some cases it was shown that an immediate signal of the law violation followed by a delayed and probable penalty was an effective substitute to immediate punishment (e.g., Altman and Krupsaw, 1983; Perry et al., 2002). This claim is relevant to the enforcement of the speed limit, since it is conceivable to create an immediate cue (e.g., an SMS message sent to the owner of the vehicle violating the speed limit) signaling to the driver that he was caught speeding by a camera.

The aim of this study was to examine which combination of concealment and fine timing in operating speed cameras is optimal and effective in enforcing speed limits. To do so, we used a driving simulator to test the effect of four orthogonal combinations of the two variables, 'speed camera concealment' and 'feedback type': (1) overt cameras with delayed feedback (similar to the most commonly implemented scenario), (2) overt cameras with immediate feedback, (3) covert cameras with delayed feedback, and (4) covert cameras with immediate feedback. In addition, to explore the effect of time and experience on the drivers' behavior each participant drove in the same scenario three times on three different days.

2. Material and methods

2.1. Participants

Fifty-eight students of the University of Haifa participated in the experiment for monetary reward (29 women and 29 men, average age 26 years old, range 23–38). A prerequisite for participation was holding at least a 5 year driver's license. The participants were randomly divided into four experimental groups, each consisted of half men and half women: 15 participated in the condition of the overt cameras with delayed feedback; 15 participated in the condition of covert cameras with delayed feedback; 14 participated in the condition of overt cameras with immediate feedback; and 14 participated in the condition of covert cameras with immediate feedback.

2.2. Tools

The experiment took place in a partial driving simulator using STISIM Drive® software which was set to run with an automatic transmission (Fig. 1). A Logitech steering system was used, which

Fig. 1. The experiment setup. The participant is sitting in a clerical chair, holding the wheel, while the scenario is presented on a wide screen in front of her.

included a steering wheel, a gas pedal and a brake pedal. Each participant sat 2.5 m from a wide screen (3 × 2.3 m, screen resolution of 1280 × 1024 pixels, and refresh rate of 60 Hz) subtending 68° × 57° of visual angle. The rate of the data collection was 30 times per second. A speaker, providing background sounds was located behind the participant.

2.3. Scenarios

A single 24 km long scenario that simulated a suburban road with two lanes in each direction separated by a road median was programmed. Traffic signs designating the speed limit were placed at the beginning of each of three road segments on both sides of the lane. The speed limit in the first 6 km was 50 kph. For the next 12 km, it was 90 kph, and then the speed limit changed again to 50 kph for the last 6 km of the scenario. Other vehicles were on the road in the simulation, however, there was not a high volume of traffic in order to enable fluent driving. The driver's speed was measured and documented at twenty predefined locations along the road. Ten of these locations were specified as speed cameras (overt or covert, according to the experimental condition) and the other ten were specified as 'speed monitoring locations'. If the driver exceeded the speed limit near a predefined camera, he would get a monetary penalty. The speed cameras were 3-D graphic models each depicted as a grey pillar with a yellow box on top (Fig. 2a). In the covert camera scenarios, no graphic cameras were visible, but camera zone warning signs were located at the beginning of the scenario (Fig. 2b) and the speed of the driver was still monitored at the same locations.

In addition, two practice scenarios were also programmed, allowing a substantial practice with the simulator setting. The practice scenarios were identical to the experimental sessions, except for the fact that only three cameras were presented in the overt cameras conditions (instead of ten).

2.4. Bonus and penalty design

Each participant received 120 New Israeli Shekels (NIS) (about $33) for his/her participation in three sessions. In addition, they could also get an extra bonus of 10 NIS for each session (total bonus of 30 NIS). The exact bonus was dependent on a bonus and penalty balance. When the driver exceeded the speed limit near a predefined speed camera location he got a penalty, but when he exceeded the speed limit near a predefined monitoring location he got a small bonus. The rationale behind this bonus–penalty balance was twofold. On the one hand, it meant to prevent intentionally slow driving to avoid penalties, while on the other hand it also meant to better simulate real life situations, in which fast driving is often desired. In real life, a monetary fine is imposed upon getting caught exceeding the speed limit but speeding without getting caught is thrilling, exciting, and saves time, hence might be desired.

2.5. Feedback

In the 'delayed feedback' condition, an email regarding the performance was sent to the participants about two days after each session. For those who did not exceed the speed limit at all, this email was phrased: "Hello XXX, you did not get any fine in the driving simulator experiment in which you took part". For those who did exceed the speed limit, this email was phrased: "Hello XXX, you were photographed exceeding the speed limit in the driving simulator experiment in which you took part, and got a fine. Therefore, unfortunately you will not get the maximum amount of money you could earn". In contrast, in the 'immediate feedback' condition, each time a participant exceeded the speed limit near a speed camera (overt or covert) a sound of a camera shot was activated.

Fig. 2. Snapshots from the scenario: (a) a yellow speed camera can be seen to the right; (b) camera zone warning signs can be seen in both sides of the lane.

Table 1
Significant effects of the ANOVA (camera condition × feedback condition × session number) on median speed.

Speed limit	Effect	df	F	p
50	Camera condition	1, 54	138.11	$p < 0.0001$
	Feedback condition	1, 54	7.39	$p < 0.009$
	Camera condition × session number	2, 108	9.28	$p < 0.0003$
	Feedback condition × session number	2, 108	6.52	$p < 0.003$
	Camera condition × feedback condition × session number	2, 108	5.36	$p < 0.007$
90	Camera condition	1, 54	40.89	$p < 0.0001$
	Feedback condition	1, 54	5.76	$p < 0.03$
	Camera condition × session number	2, 108	3.47	$p < 0.04$
	Camera condition × feedback condition × session number	2, 108	7.06	$p < 0.002$

2.6. Procedure

The participants drove the same scenario three times in different sessions, each on a different day. The minimal period between two adjacent sessions was two days and it never exceeded four days. In the first session the participants drove in a practice scenario for half an hour to get used to the simulator, which was followed by the first experimental scenario. In the other two sessions they drove only in the experimental scenarios. The participants were informed that the scenarios included speed cameras, either overt or covert according to their condition. They were asked to follow traffic laws (i.e., lane keeping, bypass signaling, accidents avoidance, etc.). Regarding the driving speed, the participants were informed that speeding in the vicinity of a speed camera would result in a monetary fine. However, they were also informed that going faster towards the end of the scenario would result in a monetary bonus (for a detailed explanation, see Section 2.4). It should be noted that the bonus and penalty balance scheme was not revealed to the participants and that they were paid only at the end of the entire experiment.

3. Results

3.1. Measurements

Several types of measurements were calculated to test the drivers' behavior. The first was the median speed, which was calculated separately for each speed limit segment (50 kph and 90 kph). The advantage of the median over the mean is that it is less affected by extreme values, and thus, situations in which the vehicle is not moving (e.g., in a traffic jam or an accident), or in contrast, when the drivers' speed is very fast, are less influential. The second type was the coefficient of variation ('speed variance'), also calculated for each speed limit segment separately and aimed to assess the statistical dispersion of the speed measurement. The third type included two kinds of measurements specific to the drivers' behavior in the vicinity of overt speed cameras, and thus, only were measured for the 29 out of 58 participants who drove under the overt camera condition: (1) a slope of the numerical differentiation of the speed function near the camera, to assess the deceleration and acceleration before and after the camera's location. This slope measurement meant to estimate the extent to which drivers performed kangaroo driving, i.e., slowing down abruptly as they approached the overt camera and accelerating right after they had passed it. Larger slopes indicated more extreme kangaroo effects. (2) The median speed of the driver in a section called 'near camera' (segments that initiated 150 m before and ended 150 m after a location of an overt camera) vs. the rest of the segments which were in between overt cameras, 'between cameras'. The aim of this measurement was to test whether the effect of the cameras on the driving speed lasted after the driver had passed the camera, and also to assess the kangaroo effect. If this effect occurs we would expect to find a slower speed for the 'near camera' segments than for the 'between cameras' segments.

If not otherwise mentioned all these measurements were the subjects of a mixed design three factorial analysis of variance (ANOVA), with the between subjects' factors 'camera condition' (overt vs. covert) and 'feedback condition' (immediate vs. delayed), and the within subjects' factor 'session number' (first, second, or third). Also note that the various values of the statistical analyses are presented in tables to ensure a more concise report.

3.2. Median speed (Table 1)

The main effect of camera condition on the median speed was significant for both segments. The median speed was higher in the overt camera condition than in the covert camera condition. For segments where the speed limit was 50 kph, the median speed was 82.8 kph when the cameras were overt vs. 52.6 kph when cameras were covert. In segments where the speed limit was 90 kph, the median speed was 101.3 vs. 84.6 kph, respectively. The main effect of the feedback condition was also significant for both speed

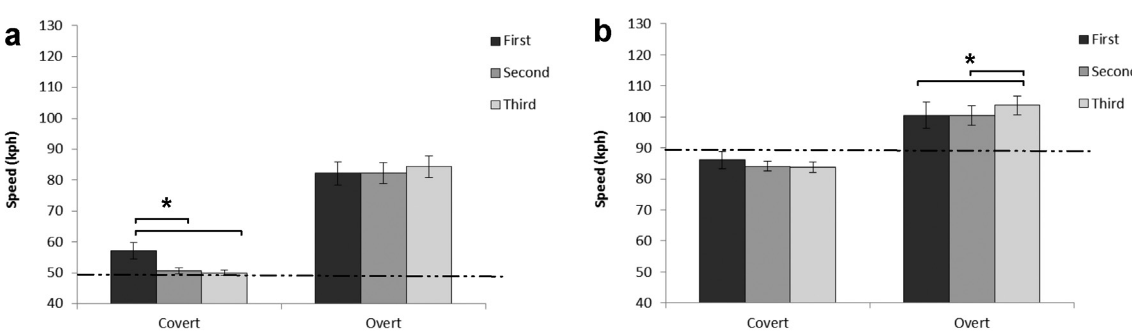

Fig. 3. Median speed as function of camera condition and session number: (a) speed limit = 50 kph; (b) speed limit = 90 kph. '*' denotes simple comparisons significant differences. The dashed line represents the speed limit. The error bars reflect standard errors.

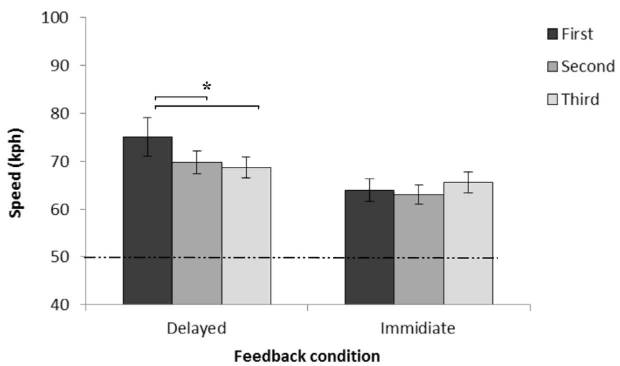

Fig. 4. Median speed as function of feedback condition and session number for segments with 50 kph speed limit. '*' denotes simple comparisons significant differences. The dashed line represents the speed limit. The error bars reflect standard errors.

segments. The median speed was higher under the delayed than the immediate feedback condition (speed limit = 50 kph: 71.2 vs. 64.2 kph; speed limit = 90 kph: 96.1 vs. 89.8 kph, respectively).

The two way interaction between camera condition and session number was also significant for both segments. Least square difference (LSD) post-hoc analysis indicated that in 50 kph speed limit segments the median speed in the overt cameras condition did not change from one session to the next (Fig. 3a), while in the covert cameras condition the median speed decreased significantly from the first session to the other two sessions ($p < 0.0001$). These results suggest that in segments where the speed limit was 50 kph, the participants in the covert cameras condition did not always keep the speed limit in the first session but learned to do so as the experiment progressed. For 90 kph speed limit segments, there was no significant change in the median speed between the three sessions with the covert camera condition (Fig. 3b); however, with the overt camera condition, the median speed significantly increased in the third session compared to the first and second sessions ($p < 0.04$). For the 90 kph segments, the participants in the overt camera condition were more willing to exceed the speed limit as they gained experience with the scenarios.

The two way interaction between feedback condition and session number was significant only for the 50 kph speed limit segments (Fig. 4). LSD post-hoc analysis showed that the median speed of the delayed feedback group was reduced significantly from the first session to the other two sessions ($p < 0.0008$). In contrast, the median speed of the immediate feedback group did not change significantly from one experimental session to the next.

The three way interaction between camera condition, feedback condition and session number was significant for both the 50 and 90 kph speed limit segments (Fig. 5a and b, respectively). LSD post-hoc analysis indicated that for both the 50 and 90 kph segments the median speed of the 'covert cameras with delayed feedback' group was reduced significantly from the first session to the other two sessions ($p < 0.02$). In contrast, the 'overt cameras with delayed feedback' group demonstrated an opposite trend, because a slight (and mostly insignificant) increase in the median speed from the first session to the other two sessions was found. Only the increase between the first and the third sessions for the 90 kph limit segments was significant ($p < 0.003$). A significant increase in the median speed of the third session compared with the second session ($p < 0.05$) was also evident in the 'overt cameras with immediate feedback' group for segments with a speed limit of 50 kph. However, the pattern of this group for the 90 kph speed limit segments was somewhat different. An almost significant reduction at the second session compared with the first one was found ($p = 0.0832$), and then an almost significant increase in the third session was also found ($p = 0.0919$). The 'covert cameras with immediate feedback' group did not exhibit any change between the sessions in both the 50 and 90 speed limit segments. For segments with a speed limit of 50 kph, the median speed barely went up above the speed limitation (the dashed line in Fig. 5) in each one of the three sessions. In the 90 kph speed limit segments, the median speed was even slower than the speed limitation and, again, there was no difference in the median speed between the three sessions.

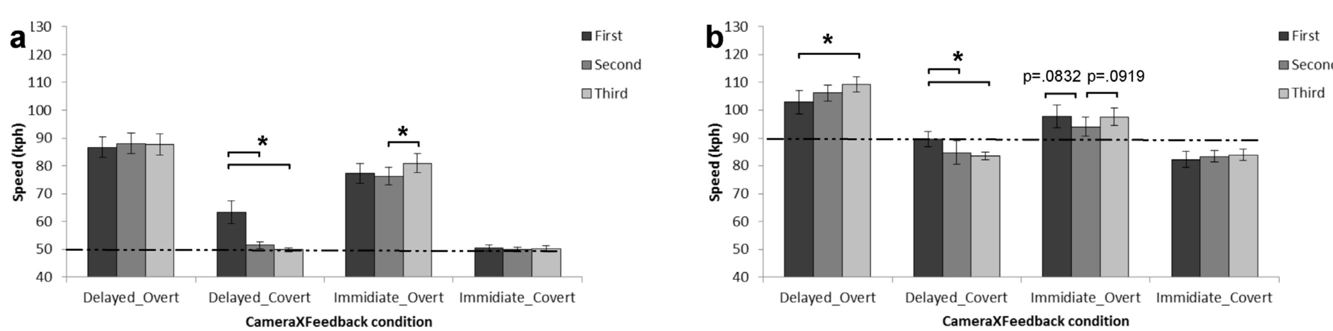

Fig. 5. Median speed as function of camera condition, feedback condition and session number: (a) speed limit = 50 kph; (b) speed limit = 90 kph. '*' denotes simple comparisons significant differences. The dashed line represents the speed limit. The error bars reflect standard errors.

Table 2
Significant effects of the ANOVA (camera condition × feedback condition × session number) on mean speed variance.

Speed limit	Effect	df	F	p
50	Camera condition	1, 54	76.19	$p < 0.0001$
	Feedback condition	1, 54	3.66	$p = 0.0610$
	Camera condition × session number	2, 108	19.67	$p < 0.0001$
	Camera condition × feedback condition	1, 54	4.14	$p < 0.05$
	Camera condition × feedback condition × session number	2, 108	5.0	$p < 0.009$
90	Camera condition	1, 54	64.48	$p < 0.0001$

This pattern implies that 'covert cameras with immediate feedback' group complied with the speed limitations throughout all three experimental sessions. All other effects did not attain statistical significance.

3.3. The mean speed variance (Table 2)

The speed variance was calculated separately for each speed limit road segment (50 kph and 90 kph) of each participant in each session. This measurement reflects the tendency of the participant to drive in a reasonably steady speed, the higher the variance the less steady the driving speed.

The main effect of camera condition was significant for both segments. The mean speed variance was higher in the overt than covert cameras condition (speed limit = 50 kph: 501.4 kph^2 vs. 83.3 kph^2; speed limit = 90 kph: 334.7 kph^2 vs. 84.5 kph^2, respectively). The main effect of feedback condition was almost significant for 50 kph speed limit segments. The mean speed variance was higher in the delayed than the immediate feedback condition (338.6 kph^2 vs. 247.1 kph^2, respectively).

The two way interaction between camera condition and session number was significant only for the 50 kph speed limit segments (Fig. 6). LSD post-hoc analysis showed that the speed variance of the covert camera condition significantly decreased from the first session to the other two sessions ($p < 0.003$). The overt camera condition showed an opposite pattern, since the speed variance significantly increased from one session to the other (all pairwise comparisons were significant at $p < 0.02$).

The two way interaction between camera condition and feedback condition was also significant only for the 50 kph speed limit segments (Fig. 7). LSD post-hoc analysis indicated that the speed variance of the overt camera condition was smaller with immediate feedback compared to delayed feedback ($p < 0.0001$). However, there was no difference in the variance between the two feedback conditions in the covert cameras condition.

The three way interaction between camera condition, feedback condition and session number was also significant for the 50 kph speed limit segments only (Fig. 8). LSD post-hoc analysis confirmed that the speed variance of the 'covert cameras with delayed feedback' group was reduced significantly from the first session to the other two sessions ($p < 0.03$). For the 'overt cameras with delayed feedback' group, an opposite effect emerged and a significant increase in the variance from the first session to the other two sessions ($p < 0.0001$) was found. A significant increase was also found between the third session and the first two sessions ($p < 0.03$) of the 'overt cameras with immediate feedback' group. Finally, the difference between the speed variance in the three

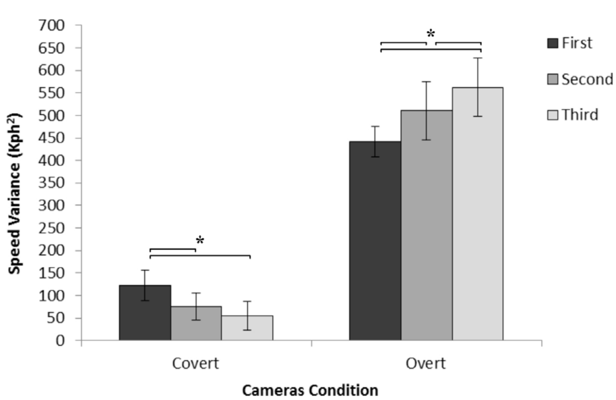

Fig. 6. The speed variance as a function of camera condition and session number in 50 kph speed limit segments. '*' denotes simple comparisons significant differences. The error bars reflect standard errors.

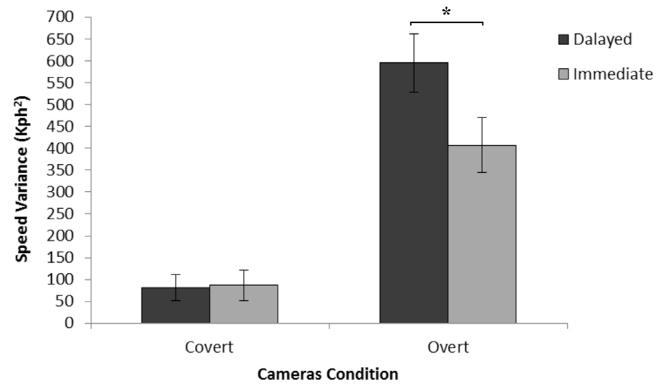

Fig. 7. The speed variance as a function of camera condition and feedback condition in 50 kph speed limit segments. '*' denotes simple comparisons significant differences. The error bars reflect standard errors.

sessions of the 'covert cameras with immediate feedback' group was not significant. All other effects did not attain statistical significance.

3.4. Mean numerical differentiation of the speed function slope measurement – the magnitude of slope in the vicinity of overt cameras (Table 3)

The slopes in the vicinity of all 10 overt cameras were calculated for each participant in each session, and the values were averaged across participants. These means were the subject of a mix design two factorial analysis of variance (ANOVA) with the between subjects factor 'feedback condition' (immediate vs. delayed) and the within subjects' factor 'session number' (first, second, or third).

The main effect of session number was significant. LSD post-hoc analysis reveals that the slope value significantly increased from the first session (0.0102) to the other two sessions (second session: 0.0124, $p < 0.02$; third session: 0.0121, $p < 0.03$). The two way interaction between feedback condition and session number was almost significant (Fig. 9). LSD post-hoc analysis showed that the slope of the delayed feedback group increased significantly from the first session to the other two sessions ($p < 0.04$). In contrast, no difference between the various sessions was found among the immediate feedback group. All other effects did not attain statistical significance.

3.5. Median speed 'near camera' vs. 'between cameras' (Table 4)

The median speed was the subject of a mix design three factorial analysis of variance (ANOVA) with the between subjects' factor feedback condition (immediate vs. delayed) and the within subjects' factors session number (first, second, or third) and camera proximity (near camera vs. between cameras). This analysis was performed separately for segments of 50 kph and 90 kph speed limits. Only effects that include camera proximity are reported.

The main effect of camera proximity was significant for both the 50 and 90 speed limit segments. For both segments, the median 'near camera' speed was slower than the 'between camera' speed (speed limit = 50 kph.: 52.4 kph. vs. 87.6 kph.; speed limit = 90 kph.: 79.7 kph. vs. 105.1 kph., respectively).

The two-way interaction between the feedback condition and camera proximity was significant for the 50 kph speed limit segments (Fig. 10a) and almost significant for 90 kph speed limit segments (Fig. 10b). LSD post-hoc analysis confirmed that in both the 50 and 90 kph speed limit segments the median 'near camera' speed was significantly slower than the 'between camera' speed.

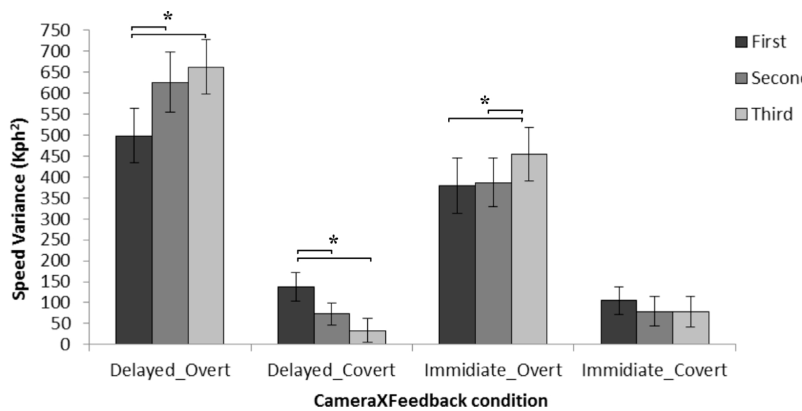

Fig. 8. Speed variance as a function of camera condition, feedback condition and session number in 50 kph speed limit segments. '*' denotes simple comparisons significant differences. The error bars reflect standard errors.

However, the difference was less prominent in the immediate feedback condition, resulting in a significant reduction in the median speed of the immediate feedback group compared with the delayed feedback group in the between cameras segments ($p < 0.0001$). Fig. 10 also shows that in the 50 kph speed limit segments the median speed in the cameras' vicinity was about 2–3 kph above the speed limit, while in the 90 kph speed limit segments the median speed in proximity of the camera was about 10 kph below the speed limit.

The two-way interaction between session number and camera proximity was significant for the 50 kph speed limit segments (Fig. 11a) and almost significant for the 90 kph speed limit segments (Fig. 11b). LSD post-hoc analysis showed that for the 50 kph speed limit segments the median speed in the 'near camera' segments decreased significantly from the first session to the other subsequent sessions ($p < 0.02$). A similar pattern was found for the 90 kph speed limit segments: the median speed in the 'near camera' segments decreased from the first session to the other subsequent sessions, but only the difference between the first and the second session was almost significant ($p = 0.0718$). In contrast, an opposite pattern was found for the 'between cameras' segments: in both the 50 and 90 kph speed limit segments the median speed significantly increased from the first and the second sessions to the third one ($p < 0.02$). These results suggest that as the drivers gained more experience with the scenario and specifically with the overt camera locations they adopted more careful driving in proximity of the cameras, decreasing their speed (and even more than necessary for the 90 kph speed limit segments). However, between the cameras they were more reckless in their driving speeds, increasing the speed from one session to the next. These observed patterns also confirm the occurrence of the kangaroo effect. All other effects did not attain statistical significance.

4. Discussion

The current study aimed to explore the optimal operation mode of speed cameras that would most effectively influence drivers to continuously adhere to the designated speed limit. Using a driving simulator, we orthogonally tested two key variables in combinations of four groups: overt vs. covert 'speed camera type' and immediate vs. delayed 'feedback type'.

We found that those drivers in the 'covert cameras with immediate feedback' group did not exceed the speed limit and kept a low speed variance throughout all three sessions. In contrast, drivers in both the 'overt cameras' groups (with immediate and delay feedback) exceeded the speed limit most of the time, excluding when driving in proximity of overt cameras. Additionally, their speed variance was very high, which tended to increase along with their speed, from session to session. The current study shows that both median speed and speed variance were higher with overt than covert cameras, hence it can be reasonably concluded that the covert cameras more effectively promote adherence to the designated speed limit. Moreover, the findings suggest that implementing a covert camera system along with immediate feedback is more conducive to drivers maintaining steady speeds at the permitted levels. Finally, the 'covert cameras with delayed feedback' group exceeded the speed limit in the first session but learned post-feedback (between the first and the second sessions) to maintain their speeds below or at the speed limit in the subsequent two sessions. Similar reduction pattern from the first to the other two sessions was also found in the speed variance measurement.

Focusing on the kangaroo effect of the groups that drove in the overt cameras condition revealed that both the 'delayed feedback' and 'immediate feedback' groups exhibit a kangaroo effect throughout all three sessions. However, only the 'delayed feedback' group showed also an increase from one session to the next in the magnitude of the slope of the numerical differentiation of the speed. Because the current study used a driving simulator, it enabled the direct measurement of the

Table 3
Significant effects of the ANOVA (feedback condition × session number) on the mean numerical differentiation of the speed function slope measurement.

Effect	df	F	P
Session number	2, 54	3.92	$p < 0.03$
Feedback condition × session number	2, 54	2.72	$p = 0.0751$

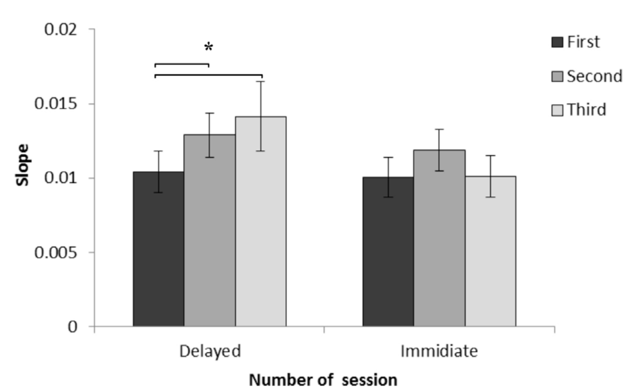

Fig. 9. Slope of the numerical differentiation of the speed as a function of feedback condition and session number. '*' denotes simple comparisons significant differences. The error bars reflect standard errors.

Table 4
Significant effects of the ANOVA (camera proximity × feedback condition × session number) on median speed 'near camera' vs. 'between camera'.

Speed limit	Effect	*df*	*F*	*p*
50	Camera proximity	1, 27	241.68	$p < 0.0001$
	Feedback condition × camera proximity	1, 27	5.97	$p < 0.03$
	Camera proximity × session number	2, 54	10.09	$p < 0.0003$
90	Cameras vicinity	1, 27	92.58	$p < 0.0001$
	Feedback condition × camera proximity	1, 27	3.44	$p = 0.0746$
	Camera proximity × session number	2, 54	2.72	$p = 0.0751$

kangaroo effect; thus, the current findings clearly suggest that such a kangaroo effect takes place quite often, as suggested in previous studies (e.g., De Pauw et al., 2014a,b; Liu et al., 2011). Other studies demonstrated that the effect of the overt camera on speed compliance and on collision rates and severity was limited to 500–1000 m near the camera (Keenan, 2002; Nilsson, 1992 in Elliott and Broughton, 2005). Our results support these findings that the positive impact of overt speed cameras is observed primarily in close proximity to the cameras themselves.

Although both the 'overt cameras with immediate feedback' and 'overt cameras with delayed feedback' groups exceeded the speed limit between cameras, the median speed in these segments was lower for the immediate than delayed feedback group. In addition, for the 'covert cameras with immediate feedback' group the feedback prevented exceeding the speed limit right from the first session in contrast to the 'covert cameras with delayed feedback' group. Dijksterhuis et al. (2015) also found a similar pattern in the context of implementing a Pay-As-You-Drive insurance, where drivers are charged directly according to their driving performance. These findings, along with the main effect of feedback condition with median speed and speed variance measurements, suggest that immediate feedback has an independent effect on drivers' speed and that it can serve as speed moderating treatment. In fact, de Waard and Brookhuis (1997) used auditory messages about speed violation and found a sharp decrease in the number of speed violations, as well as a decline in the extent to which the speed limit was exceeded. These were found in both an on-road experiment that used instrumented vehicle and in a driving simulator experiment. Similarly, Merrikhpour et al. (2014) tested a real-time feedback–reward system in a field study and found that during the intervention phase the speed limit compliance increased significantly.

There are some limitations to the current study that should be considered. On the one hand, a simulator study that simulates real-life settings does not provide the controlled environment that a laboratory study does, and therefore it might introduce possible confounding variables (Caird et al., 2008). However, the study's aim was to test the influence of speed cameras and feedback type

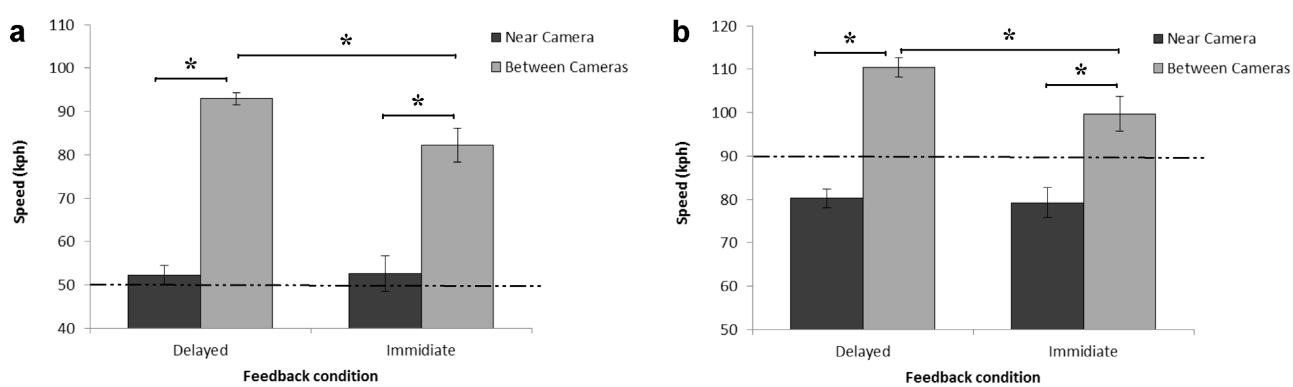

Fig. 10. Median speed as function of camera proximity and feedback condition: (a) speed limit = 50 kph; (b) speed limit = 90 kph. '*' denotes simple comparisons significant differences. The dashed line represents the speed limit. The error bars reflect standard errors.

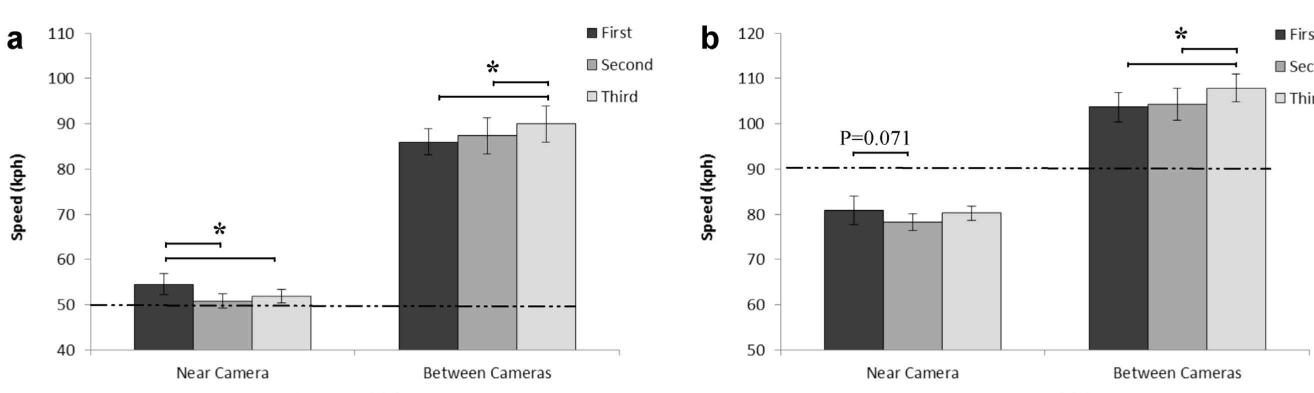

Fig. 11. Median speed as function of cameras proximity and session number: (a) speed limit = 50 kph; (b) speed limit = 90 kph. '*' denotes simple comparisons significant differences. The dashed line represents the speed limit. The error bars reflect standard errors.

on drivers' speed, which can only be obtained through field or driving simulator study. On the other hand, driving in a simulator is not the same as driving in a real-life setting (e.g., Blana, 1996; Mullen et al., 2011). For example, a sharp deceleration in the face of an overt camera can result in a rear-end accident in real driving settings, thus drivers might be more careful in real driving than while driving in a simulator. If this is true, then the magnitude of the kangaroo effect found in this study may be more exaggerated than in a real-life driving situation. Nevertheless, given that a similar pattern of a kangaroo effect has been found in a field study (De Pauw et al., 2014a), implies that it is reasonable to assume that this effect often occurs in reality, even if its magnitude might be smaller than what we found here. The atypically high speeds observed in the 50 kph speed limit segments of the overt camera scenarios, may possibly be an indication that these areas did not optimally simulate urban areas. Yet another explanation for this finding may be that the drivers were not always fully aware of the speed limit in the various segments of the simulation. It is possible that in some cases, the drivers thought or assumed that the limit was 90 kph when it was actually 50 kph. Furthermore, many considerations that drivers take into account in real life driving situations cannot be fully experienced or recreated in a driving simulation. For example, on the one hand in real life speeding might be thrilling, exciting, and saves time. On the other hand speeding in real life can end with a car accident, or with getting fines that are usually quite high. Both of these consequences are certainly undesirable. These factors are absent when driving in a simulator. We did, however, tried to mimic the various real-life incentives and concerns by employing a bonus and penalty scheme in the current study. Note that the participants were not aware of this scheme, thus, they were unable to adjust their behavior according to the highest perceived utility. Yet there is still a possibility that the experimental instructions themselves might have caused the participants to deviate from real-life driving.

To summarize, the results of the current experiment suggest that an implementation strategy consisting of covert speed cameras combined with immediate feedback to the offender, is potentially an optimal way to prevent drivers from exceeding the speed limit and maintaining speeds at or below the speed limit for the entire distance. The results also emphasize the problematic nature of overt cameras, that seemingly encourage driving behaviors leading to a kangaroo effect, as well as, increased risks associated with increased speeding between camera locations as a result of the learned location of the cameras. All of this suggests that overt cameras are not optimal compared to covert cameras, as they do not prevent drivers from exceeding the speed limit, except for in proximity of the cameras' locations.

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