Taking the load off: investigations of how Adaptive Cruise Control affects mental workload.

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Taking the load off: investigations of how Adaptive Cruise Control affects mental workload.

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It has been posited that Adaptive Cruise Control (ACC) represents a new generation of vehicle automation, in that it has the potential to relieve drivers of mental as well as physical workload. The results of previous research however, have raised some confusing issues about the specific effects of Adaptive Cruise Control (ACC) on driver mental workload (MWL) – some studies report reduced MWL compared to manual driving, while others find no effect. Two hypotheses are proposed in an attempt to explain these discrepancies: a) that any potential MWL reductions due to ACC could be masked by the overriding influence of steering demand; or b) that the tasks designed in some experiments do not exploit the adaptive nature of the ACC system, therefore precluding any potential benefits. Two related experiments were designed to test these hypotheses. It was found that the main reason for the discrepant findings was the nature of the driving task chosen – constant-speed tasks do not realise the mental workload benefits of ACC. Future researchers using ACC devices are advised to use variable-speed tasks to ensure that all aspects of device functionality are covered.

Keywords: Adaptive Cruise Control, driving simulator, mental workload, vehicle automation

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1. INTRODUCTION

'Adaptive Cruise Control (ACC) heralds a new generation in vehicle automation' (Stanton et al. 1997:. 150). ACC has the capability to maintain a set speed, similar to conventional cruise control (CC), but also to detect other vehicles in front and adjust speed to maintain a set headway. So, whereas CC simply relieves the driver of physical workload (keeping the foot on the accelerator pedal), ACC removes some of the decision-making elements from driving (perception of closing speed, time-to-contact; Stanton et al. 1997, Stanton and Young 1998). As such, it has the capability to relieve the driver of some mental workload (MWL). An analysis of the literature however, seems to suggest some confusion about the effects of ACC on driver MWL. This may be due to issues of experimental design in previous studies, or it may be that the effects of ACC genuinely vary in different task situations. Either way, the problem needs to be addressed if future experiments are to be designed appropriately. Knowing the exact effects of ACC on driver MWL would also have significant practical applications, as next-generation systems may well end up being designed around the workload needs of the driver.

Previous research specifically addressing the relation between ACC and driver MWL is relatively scarce at present, and has been reviewed by Young and Stanton (2002). Most studies have used experienced driver groups, and either a subjective measure of MWL or a secondary task measure of spare capacity. Nilsson (1995) and Ward et al (1995) used the NASA-TLX in their studies to measure subjective MWL. Using ACC did not affect the Overall Workload ratings in either of these studies, when compared to normal driving. Similarly, Young and Stanton (2002) found that ACC did not affect spare attentional capacity as measured by a visuo-spatial secondary task. In contrast, Stanton et al. (1997) used the same secondary task measure and concluded that MWL was significantly reduced when drivers engaged ACC. This is despite the fact that the latter study used the same simulator and a similar driving task as Young and Stanton (2002). The only substantial differences were that Stanton et al. (1997) used two minute trials (instead of 10 minute trials), and the lead vehicle travelled at a constant 80 kph (50 mph (instead of 112 kph (70 mph))). However, a notable flaw in their design could explain why Stanton et al. (1997) found superior secondary task performance in the ACC condition. Due to the nature of the study, investigating failure of the ACC system, proper counterbalancing of the conditions was not possible. Participants always drove the Manual condition first, followed by ACC, and finishing with the ACC failure condition. The improvement in secondary task performance is therefore more likely due to a practice effect rather than differences in mental demands between the conditions.

An explanation for the conflicting findings, then, relates to the experimental design. Young and Stanton's (2002) design involved following a constant-speed lead vehicle along a track which was a mixture of curved and straight sections. When compared with drivers of higher and lower skill levels (Young and Stanton, 2004), there seemed to be something special about the Expert driver group, in that many of their performance data were quite distinct from the other three skill groups. Combining this information with the knowledge that ACC alone did not affect any of the Expert MWL results, the plausible conclusion emerges that processing of the longitudinal control task had become completely attention-free (i.e. automatic) for Expert drivers. Perhaps, then, the task used by Young and Stanton (2002) was not appropriate to highlight any MWL effects for Experts using ACC. Rather than attempt to replicate the experiment of Stanton et al. (1997) with its design flaw, it was thought that an exploration of the driving task of Young and Stanton (2002) was in order.

The results of Young and Stanton (2002) clearly indicated that steering imposed a much heavier load on participants than longitudinal control for that task situation. Indeed, the effect could have been such a significant one that it masked any MWL advantage of using ACC. This explanation would account for the fact that, when the steering load was no longer a factor (i.e. steering had been automated), ACC did significantly reduce MWL. Minimizing the steering load in manual driving, then, may reveal effects of ACC which were not previously observable. Alternatively, it could be the case that the driving task – following a constant-speed lead vehicle – was not a fair test of the 'adaptiveness' of the ACC system. This task is more akin to using standard CC. Increasing the demands of longitudinal control would test this explanation.

Two new experimental designs were therefore constructed for the present study, using the same four levels of automation as Young and Stanton (2002). These were: Manual (participant controls speed and steering), ACC (participant controls steering only), Active Steering (AS – participant controls speed only), and ACC+AS (both speed and steering are automated – essentially a fully automated drive). Only Expert drivers were recruited, as these participants have commonly been recruited in previous studies. The two manipulations – minimizing steering load and increasing longitudinal load – were varied one at a time, to isolate their effects, and evaluate each explanation independently. Experiment 1 used a constant-speed vehicle following task (as did Young and Stanton 2002), but the track design was altered to a continuously straight road. As such, the lateral demands of keeping the vehicle in its lane were minimized. This is similar to using AS, so this experiment would predict reduced MWL in the ACC and ACC+AS conditions (which are similar to each other), but no difference between Manual driving and using AS. These predictions are illustrated in figure 1.

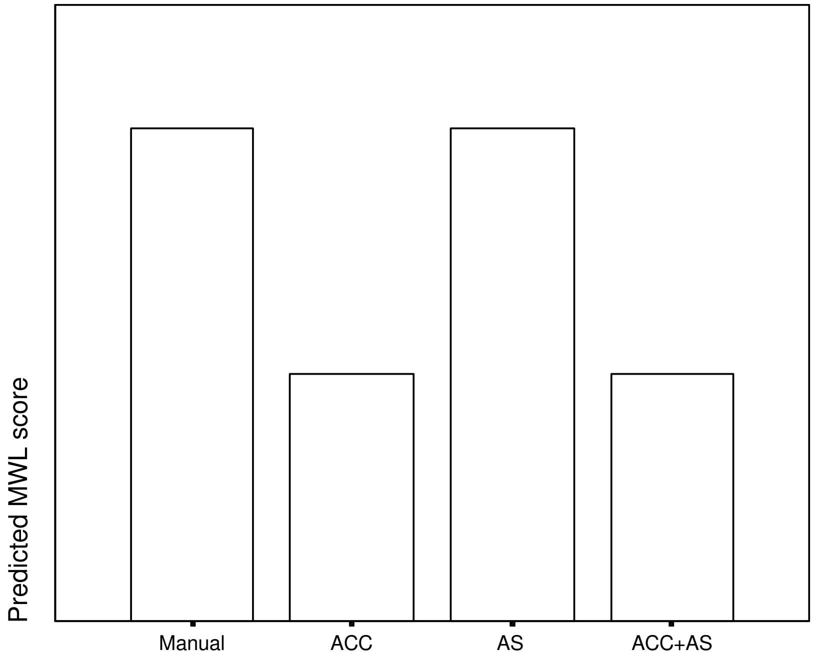

Figure 1. Predicted MWL scores across automation conditions, experiment 1. These predictions are based on the hypothesis that ACC will only reduce MWL if steering demands are minimized

Experiment 2 used the same mixed track layout as Young and Stanton (2002), but a variable-speed lead vehicle was introduced. This imposes additional longitudinal demand, so the prediction of this study is a stepwise reduction in MWL across the Manual, ACC, AS, and ACC+AS conditions (assuming that steering is still more demanding than the additional longitudinal task). Again, these predictions are represented in figure 2.

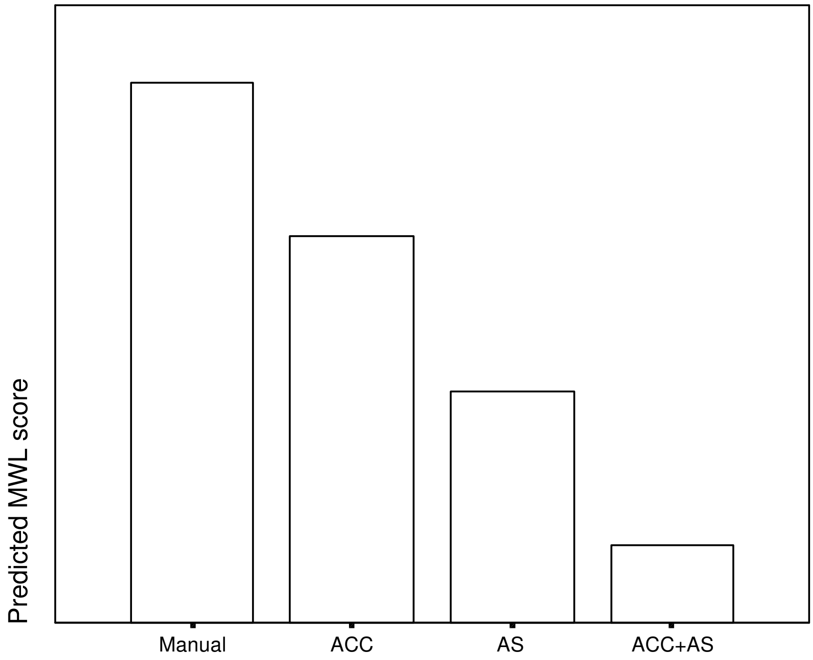

Figure 2. Predicted MWL scores across automation conditions, experiment 2. These predictions are based on the hypothesis that ACC will only affect MWL if longitudinal demands are nontrivial

2. EXPERIMENT 1: STRAIGHT ROADS

2.1. Method

2.1.1. Design. Experiment 1 was conducted in order to determine whether any ACC effect on MWL in Young and Stanton's (2002) study may have been masked by the dominant influence of steering. Therefore, participants were required to drive on a simple straight road for 10 minutes in each of the four automation conditions (Manual, ACC, AS, ACC+AS). This removes most of the steering demand, making the MWL measurements more sensitive to longitudinal demands. If there is an effect of ACC, it should be revealed here. All other conditions and instructions remained as they were set by Young and Stanton (2002).

The design was completely within-subjects, with Expert drivers (i.e. those with a full UK driving licence) recruited as participants. The order of presentation of automation conditions was appropriately counterbalanced to prevent practice effects. Dependent measures for this study included the primary task measures of longitudinal and lateral control (see below), and a visual-spatial secondary task to measure spare capacity. Total number of correct responses was the dependent variable for the secondary task. In addition, the NASA-TLX (Hart and Staveland 1988) was used to measure subjective MWL, in order to compare with previous studies using this technique (Nilsson 1995, Ward et al. 1995). Overall Workload (OWL) was the dependent variable, calculated as the arithmetic mean of the raw scores on each of the six TLX subscales.

2.1.2. Participants. There were 12 participants (four of which were males) in experiment 1. The mean age of participants was 24.7 years (SD = 6.79). Participants had held their full driving licences for a mean of 7.04 years (SD = 6.80), and drove 6500 miles per year on average (SD = 4079). The annual mileage statistics for this set of participants are somewhat lower than the national mean, due to the dependency upon student samples. However, the total exposure of participants was considered high enough to qualify them as Expert drivers.

Recruitment of participants took place via posters around the University of Southampton campus, and through the participant pool of the Department of Psychology. The ethical protocols of the Department of Psychology and of the British Psychological Society were adhered to at all times.

2.1.3. The Southampton Driving Simulator (SDS). The SDS is a medium-fidelity, fixed-base driving simulator. The simulator consists of the front half of a Ford Orion. The steering wheel, accelerator and brake pedal produce analogue voltages. Appropriate hardware reads these voltages and converts them into digital signals to be fed into the simulation computer. An Acorn Archimedes computer runs the simulation and generates the display image. A medium-resolution colour monitor displays a view of the road and a simulated instrument panel. The resolution of the display limits the visibility range to 200 metres, at which distance another vehicle is one pixel wide. The refresh rate is 25 frames per second. The area of the screen occupied by road view is approximately 2m wide by 1.1m tall, and approximately 2.9m from the participant's eyes. The visual angle subtended at the eyepoint is therefore approximately 40º horizontal by 20º vertical. The display shows: the single-carriageway road, in solid colour with a central broken white line; other traffic in both directions; and simple roadside objects such as speed limit signs. Collisions with other vehicles or the edge of the road are detected and lead to simulated crashes. Other vehicles follow a fixed path with scripted speed changes.

The SDS software records data at a rate of 2Hz. The following data are logged: speed, lateral position on the road, distance from the vehicle in front, distance from oncoming vehicle, steering wheel and pedal positions, and collisions. The simulator was set up to run with automatic transmission at all times.

2.1.4. Procedure. Participants were allowed a 15-minute practice run, followed by the experimental instructions on the driving task and operation of the automation devices for whichever condition they were in. The secondary task was explained and an instruction to 'attend to it only when they felt they had time to do so' was emphasized, in order to minimise secondary task interference. Participants were shown examples of secondary task stimuli to satisfy the experimenter that they understood how to respond. The four automation conditions were presented to the participants according to the counterbalanced design.

In all of the experimental conditions, participants were faced with a single-carriageway road. The track was a simple straight road, with no hills or wind gusts to disturb longitudinal or lateral control. Participants were instructed to first catch up and then follow a leading vehicle, which was travelling at a constant 112 kph (70 mph) (cf. Young and Stanton, 2002), for the duration of the trial (10 minutes). There were no other vehicles in the participants' lane (so no overtaking was necessary), although oncoming traffic was encountered infrequently, encouraging participants to remain in their own lane. Participants were required to maintain a constant distance from the lead vehicle, although the choice of that distance was left to the individual. There were a number of advantages to this approach. Firstly, it meant that participants did not have to disengage the automatic devices (for instance, in order to overtake), thus avoiding contamination of conditions. Secondly, following a car motivated participants to drive at a relatively constant speed, thereby controlling objective demand across conditions. Otherwise, participants may have compensated for increased workload by reducing speed, which again would contaminate results. Finally, a constant speed implied that participants all drove approximately equal distances, again controlling for workload and attention differences which may otherwise have been incurred.

At the end of each 10 minute trial, participants completed the NASA-TLX (with instructions to only rate the driving task, not the combination of primary and secondary tasks), and were informed of the conditions for the following trial. When all four trials were completed, participants were thanked for their time and debriefed about the purpose of the experiment. The whole procedure lasted approximately 75 minutes.

2.1.5. Data reduction. For an assessment of driving performance, evaluative measures of longitudinal and lateral control were needed. Longitudinal control measures involve speed and headway. However, simple measures of location (i.e. mean, median) do not necessarily provide evaluative information about how well participants are performing. Given the instructions to participants (maintain constant speed and headway), it would be logical to adopt a measure of consistency (or rather, inconsistency) for these variables. Fortunately, Bloomfield and Carroll (1996) described such a measure, in their derivation of instability. 'A linear equation that is the line of best fit for a series of points on the track of a vehicle can be used to describe the position of the vehicle relative to the center of the lane' (Bloomfield and Carroll 1996: 336). A similar line can be calculated for vehicle speed. The sampling rate of the SDS allows such equations to be calculated for the 1200 data points on each of the speed and headway variables. The standard error around this line represents the driver's ability to maintain stability in the measure. This is a better measure of driving performance than standard deviation, as it reflects the drivers' consistency in their own performance, rather than deviation from an absolute measure (J. R. Bloomfield, personal communication, December 15 1999).

For lateral control, it was considered that instability measures would not be an appropriate reflection of driving performance on a road which involves both curved and straight sections. Popular measures of lateral control (such as instability, RMS error, or time-to-line-crossing) assume that 'good' driving performance is characterised by the vehicle remaining consistently in the centre of the lane. However, modern driving techniques (e.g. Coyne 1994) advocate a shallow trajectory when negotiating curves (i.e. approach on the outside of the curve, aim for the apex, then drift out on exit). This strategy has the effect of 'straightening' the curve, improving stability of the car as well as driver's vision. Good driving is therefore not necessarily characterized by maintaining a constant lane position, so the usual measures of lateral control will be confounded. Instead, then, simple measures of lane excursions were used to evaluate lateral control, with the assumption then being that good driving performance is rewarded with fewer lane excursions. The total number of lane excursions, and time spent out of lane, were the dependent variables for lateral control. All of the driving performance measures were filtered for outliers and extreme values, and these data points were removed prior to analysis.

2.2. Results and Discussion

2.2.1. Primary task data. A repeated measures ANOVA of mean number of lane excursions showed a significant effect of automation ($F_{3,30} = 8.31$, $p < 0.001$), which appeared to be due to the use of AS. Simple contrasts showed that the difference between the Manual and ACC conditions was nonsignificant, whilst lane excursions decreased in the AS ($F_{1,10} = 7.49$, $p < 0.05$) and the ACC+AS conditions ($F_{1,10} = 7.49$, $p < 0.05$). The F-rations are identical because there were no lane excursions in either the AS or ACC+AS conditions, so the comparisons with the manual condition were exactly the same. The descriptive data are presented in figure 3.

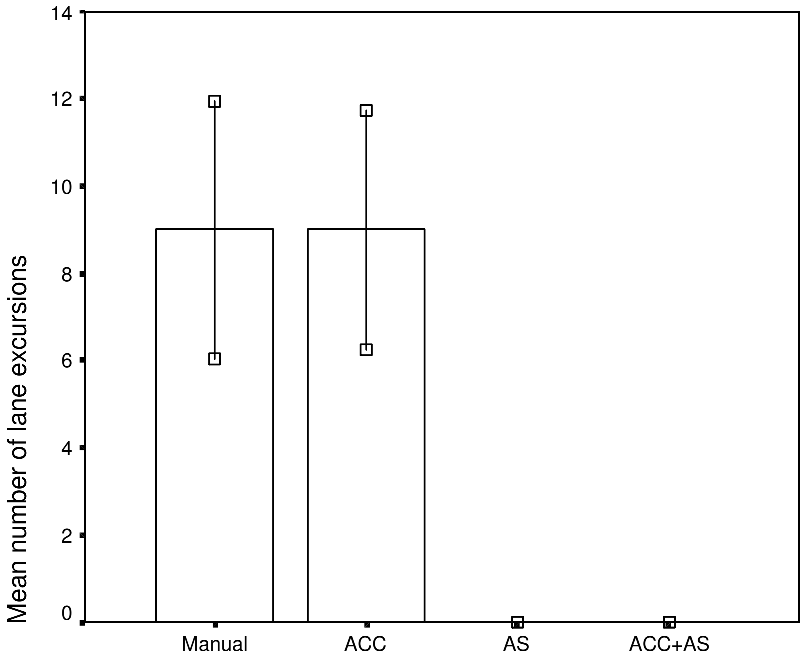

Figure 3. Number of lane excursions across automation conditions. Error bars represent one standard error

Time spent out of lane displayed exactly the same pattern. A significant effect of automation ($F_{3,30} = 6.46$, $p < 0.005$) was due to no time out of lane in the AS ($F_{1,10} = 5.84$, $p < 0.05$) and ACC+AS conditions ($F_{1,10} = 5.84$, $p < 0.05$), compared to Manual driving. There was no difference between the Manual and ACC conditions. These data are presented in figure 4.

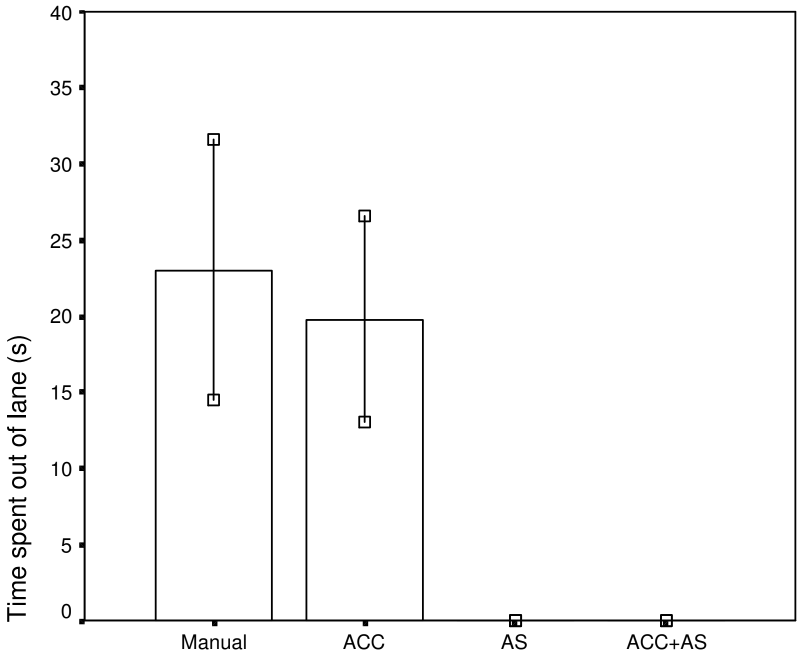

Figure 4. Time spent out of lane across automation conditions. Error bars represent one standard error

It is clear from these two results that AS is far better at controlling lateral position than a human driver. This was true despite the fact that steering demands were minimized on the straight road design of this experiment. Moreover, the more interesting comparison is between the Manual and ACC conditions, when lateral control was governed by the human in each case. It seems that the ACC system has no effect on human lateral control. In other words, steering performance was equivalent whether or not automation was used to relieve other driving subtasks.

Speed instability produced a spurious result. There was a main effect of automation ($F_{3,21} = 3.95$, $p < 0.05$), although none of the specified contrasts reached significance. Post-hoc investigations revealed a significant increase in instability from the ACC condition to the ACC+AS drive ($F_{1,7} = 8.07$, $p < 0.05$). Mean values for the Manual, ACC, AS, and ACC+AS conditions are presented in figure 5.

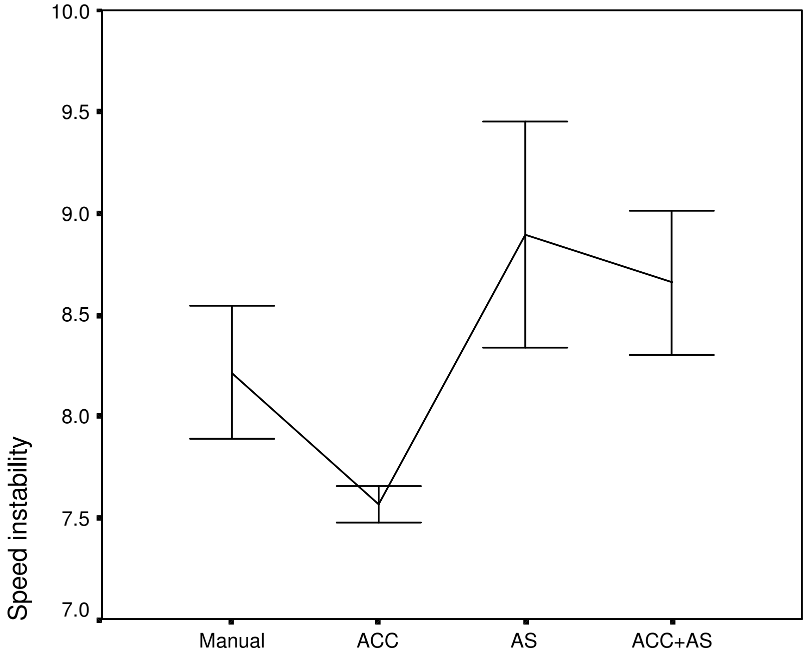

Figure 5. Speed instability across automation conditions. Error bars represent one standard error

Headway instability produced slightly clearer statistics, although the results are probably still spurious. The main effect of automation ($F_{3,18} = 14.4$, $p < 0.001$) was due to increased instability from the Manual to the ACC+AS condition ($F_{1,6} = 20.6$, $p < 0.005$). Mean values for headway instability are presented in figure 6.

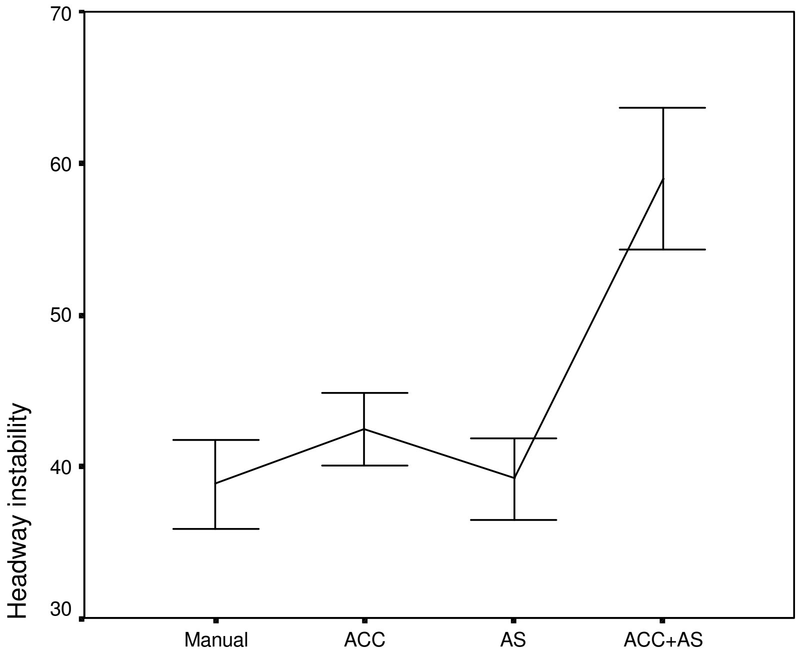

Figure 6. Headway instability across automation conditions. Error bars represent one standard error

It is not clear why speed and headway instability increased in the ACC+AS condition. ACC is designed to maintain a consistent headway, and the lead vehicle travelled at a constant speed, so there should not have been an increase in instability from a non-ACC condition to an ACC-assisted drive. These results are most likely due to some spurious data in the ACC+AS condition which escaped the filtering procedure. If the ACC+AS results are disregarded, it would appear that on a straight road, humans are equally capable of maintaining constant speed and headway as the ACC device. In Young and Stanton's (2002) experiment, longitudinal instability was generally reduced only in the ACC+AS drive. Thus it might be concluded that driving on a curved track increases longitudinal instability. Drivers were probably slowing down for corners or, in the case of the ACC condition, either disengaging

ACC or drifting out of lane such that the system lost its target and attempted to reacquire set speed.

2.2.2. Secondary task data. A repeated measures ANOVA was used to analyse the secondary task scores in each condition. Number of correct responses was the dependent variable, and level of automation was the independent variable. Repeated contrasts were used to determine whether there were any differences between adjacent levels of automation.

There was a significant effect of automation on the secondary task score ($F_{3,33} = 15.7$, $p < 0.001$). Contrasts revealed no difference between Manual and ACC conditions, but there was a significant increase in the AS condition ($F_{1,11} = 8.76$, $p < 0.05$), and a further increase in the ACC+AS condition ($F_{1,11} = 7.69$, $p < 0.05$). Mean numbers of correct responses in each of the Manual, ACC, AS, and ACC+AS conditions are plotted in figure 7.

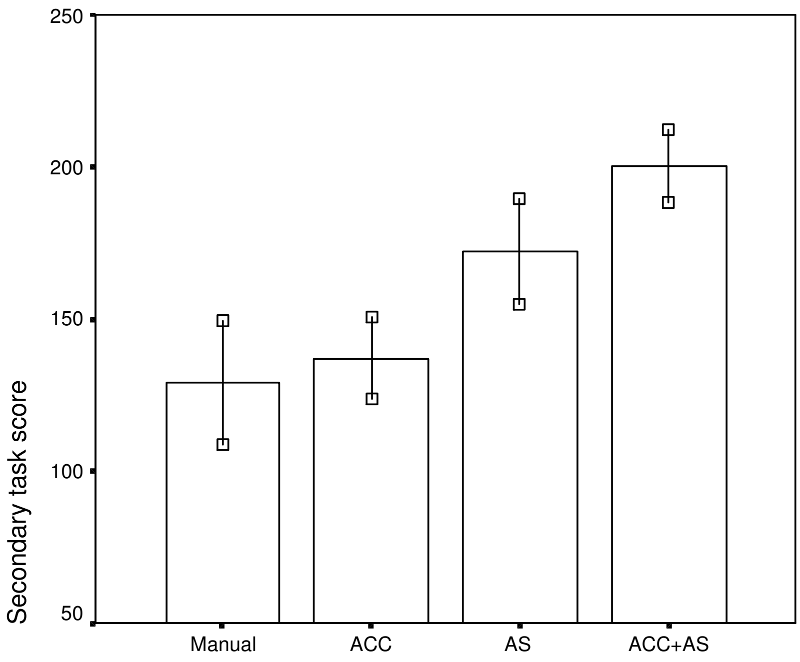

Figure 7. Secondary task scores across automation conditions. Error bars represent one standard error

These data mirror those found by Young and Stanton (2002). Therefore, minimizing lateral demands does not release any extra spare capacity when using ACC. The hypothesis that the heavy demands of steering may have masked a MWL effect of ACC is not supported, at least as far as the performance data are concerned. Note also that the secondary task scores accord well with the primary task data. Longitudinal control was no better when ACC was in command than if the human controlled speed. As such, relieving the driver of this task did not decrease the driving demands, supporting the notion that constant-speed driving is processed in a fully automatic way for Expert drivers. However, there was still a puzzling increase in spare capacity in the ACC+AS condition. Perhaps, in the AS condition, participants were periodically checking the speedometer or road view as uncertainty built up about the road situation (cf. Senders et al. 1967). Even occasional glances could sufficiently disrupt secondary task performance. Lateral control, on the other hand, was worse for humans than the automated system. Therefore, some improvement on this control dimension can still be made, and that is reflected in the additional spare capacity which is observed when steering is automated.

2.2.3. Subjective data. A repeated measures ANOVA of the Overall Workload (OWL) score derived from the NASA-TLX exhibited a significant effect of automation ($F_{3,33} = 24.3$, $p < 0.001$). Repeated contrasts showed a stepwise reduction from Manual to ACC ($F_{1,11} = 5.27$, $p < 0.05$), from ACC to AS ($F_{1,11} = 7.34$, $p < 0.05$), and from AS to ACC+AS ($F_{1,11} = 19.5$, $p < 0.005$). Young and Stanton (2002), however, found no significant difference in subjective ratings between the Manual and ACC conditions. Mean scores in all conditions are represented in figure 8.

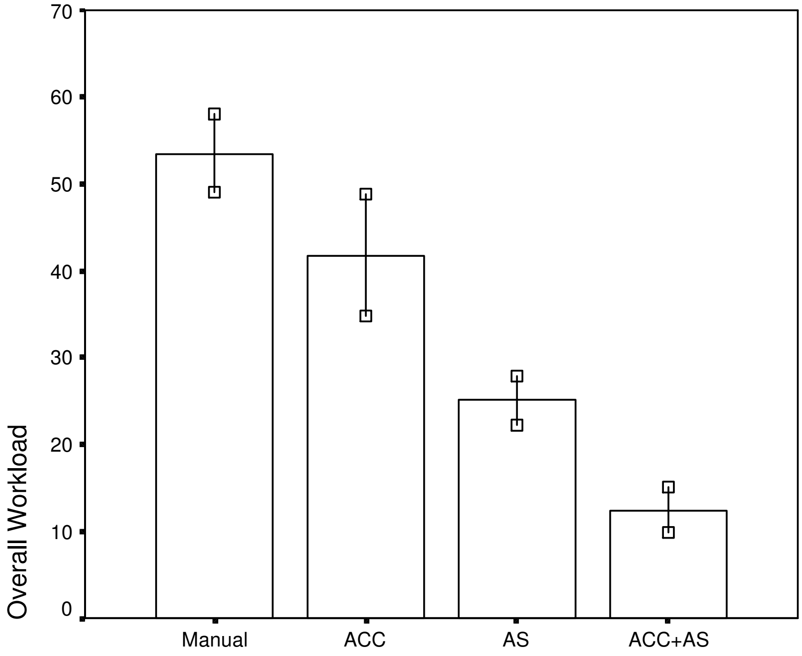

Figure 8. Overall Workload ratings across automation conditions. Error bars represent one standard error

Interestingly, participants did perceive a reduction in MWL when ACC was engaged, despite the fact that objectively (i.e. as determined from the secondary task data) the demands did not change. The masking hypothesis, initially rejected on the basis of the secondary task data, could apply to these subjective data. Actual spare capacity is not influenced by ACC, purely and simply because it does not relieve the Expert driver of any demands when the longitudinal control task is to maintain a constant speed. When other demands (i.e. steering) are high, participants understandably do not perceive a difference between the Manual and ACC conditions. However, when the steering demands are minimized, drivers do become sensitive to the absence of driving subtasks, regardless of how high the level of automaticity is. In that respect, these results are consistent with the findings of Liu and Wickens

(1994), in that the subjective instrument is sensitive to the presence of automation, whilst the secondary task revealed automatic performance.

The notion that the secondary task and subjective measures of workload are sensitive to different aspects of the same underlying construct is supported by a significant correlation between the two sets of data ($r_{48} = -0.603$, $p < 0.001$). Clearly there is some relation between spare attentional capacity and subjective reports of MWL, yet only around 36% of the variance is being accounted for in each variable. This is not surprising, since MWL is known to be such a multidimensional construct (e.g. Young and Stanton 2001). It is, therefore, quite plausible that different measures may provide similar, if not exactly the same, results.

Overall, the results from this experiment supported the hypothesis that a constant speed longitudinal control task does not pose any additional demands for Expert drivers, as automatic processing of this task has virtually reached its ceiling. This assertion could be confirmed by conducting an identical study on novice drivers for comparison. In the absence of a demanding lateral control task, participants did perceive a difference in MWL between the Manual and ACC drives. The possibility that longitudinal demands in Young and Stanton's (2002) experiment was masked by the much greater demands of steering is therefore credible.

Despite these encouraging results, the pattern of MWL data did not accurately reflect the predictions made for this experiment. In particular, there was a substantial MWL decrease when using AS, even though steering demands were minimized. Furthermore, a significant increase in spare capacity was observed in the ACC+AS condition, yet it had been concluded that longitudinal control in the present task conditions did not draw any attentional demands. Therefore, it was decided that the alternative approach – increasing the longitudinal demands – should be investigated.

3. EXPERIMENT 2: VARIABLE-SPEED LEAD VEHICLE

3.1. Method

3.1.1. Design. In the light of the results from experiment 1, it was apparent that minimizing the steering load did not reveal any advantages for ACC in terms of spare attentional capacity. Experiment 2 therefore considered an alternative hypothesis – that the task of following a constant-speed lead vehicle is not really a test of longitudinal control, and does not exploit the functionality of the ACC system. In the present experiment, the original mixed track layout of Young and Stanton (2002) was used, and a change was made to the characteristics of the lead vehicle. At pseudo-random intervals and without warning, the lead car would firmly brake (with brake lights illuminated) until it reached a speed of about 48 kph (30 mph), when it would accelerate again to maintain 112 kph (70 mph). The participant's task was to match the speed of the lead vehicle, staying behind it and trying to maintain a constant headway as before. In this case, the additional longitudinal demands should lead to a MWL reduction when ACC relieves the participant of this task.

The randomization algorithm for lead car braking intervals followed a cyclic pattern. A random number generator was used to select five intervals, ranging from 14s to 54s, and totalling 183s. These five intervals constituted one cycle, and therefore, in a 10 minute trial, three complete cycles were used.

As with experiment 1, the design was completely within-subjects, focusing on Expert driver participants. The design was counterbalanced to account for order effects in presentation of the levels of automation.

The standard primary task, secondary task, and subjective MWL measures were used as dependent variables. Primary task variables included the evaluative performance measures of longitudinal and lateral control, while the secondary task and subjective variables were as used in the previous experiment.

3.1.2. Participants. Of the 12 participants in experiment 2, eight of these were males, and the mean age of all participants was 28.6 years (SD = 7.60). Mean annual mileage was 7167 (SD = 4489), and participants had passed their driving test on a mean of 9.75 years ago (SD = 7.04). Again, the low mean annual mileage statistics were notable, but not considered to be a problem in terms of total exposure.

Participants were recruited by means of posters around the University of Southampton campus, as well as through the Department of Psychology's own participant pool. The experiment was authorised by the ethical committee in the Department of Psychology, and British Psychological Society standards for the use of human participants were met.

3.1.3. The Southampton Driving Simulator (SDS). The SDS as described in experiment 1 was again used for this study. The only difference in the set-up this time was in the track layout. Whereas in experiment 1 the road was purely straight, this time it was a mixture of curved and straight sections, as used by Young and Stanton (2002, 2004).

3.1.4. Procedure. Experiment 2 used the same procedure as the previous study. A 15-minute practice run was followed by the experimental instructions for whichever condition participants were in. The secondary task was introduced with example stimuli, and participants were explicitly instructed attend to it only when they felt they had time to do so.

Automation conditions were presented to the participants in a random order, according to a counterbalanced design. The driving task was rated on the NASA-TLX at the end of each trial, and a full debriefing was given at the end of the experiment.

3.1.5. Data reduction. The data reduction procedure as described in Experiment 1 was used to collect data on the evaluative driving performance variables of number of lane excursions, time spent out of lane, speed instability, and headway instability. Outliers and extreme data points on all of these variables were deleted on a case-by-case basis. Number of correct responses on the secondary task during the 10-minute trial was the dependent variable for spare attentional capacity. The overall workload scale of the TLX, derived from the six subscales, was treated to analysis.

3.2. Results and Discussion

3.2.1. Primary task data. The repeated measures ANOVA for number of lane excursions showed a significant effect of automation ($F_{3,27} = 34.9$, $p < 0.001$). The simple contrasts revealed that this was due to a greater number of excursions in the Manual condition than in the AS ($F_{1,9} = 42.2$, $p < 0.001$) and ACC+AS conditions ($F_{1,9} = 45.2$, $p < 0.001$). There was no difference between Manual and ACC conditions. Mean numbers of lane excursions in each condition are presented in figure 9.

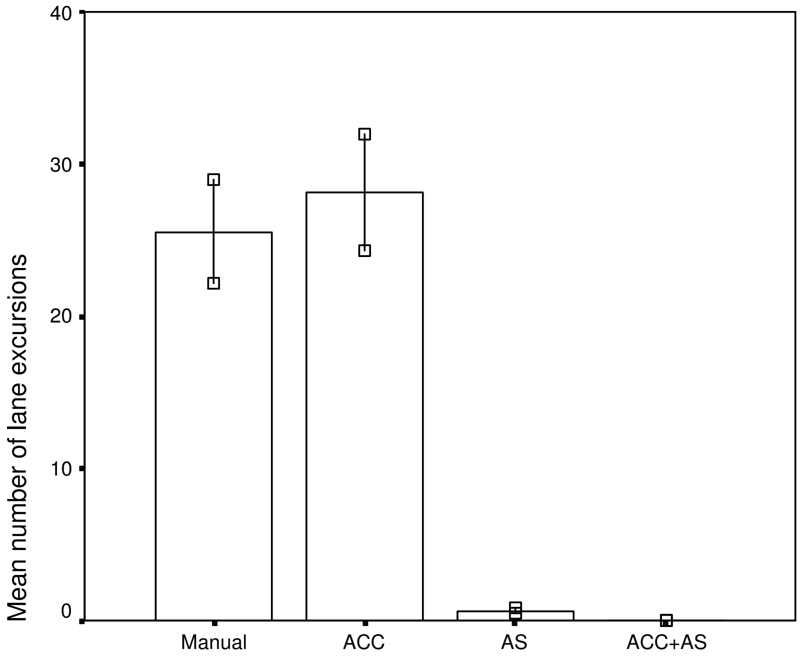

Figure 9. Number of lane excursions across automation conditions. Error bars represent one standard error

Time spent out of lane exhibited the same pattern as number of lane excursions. A significant effect of automation ($F_{3,30} = 22.3$, $p < 0.001$) was due to more time spent out of lane in the Manual condition than in each of the AS ($F_{1,10} = 25.8$, $p < 0.001$) and ACC+AS conditions ($F_{1,10} = 26.0$, $p < 0.001$). The difference between Manual and ACC conditions was nonsignificant. Means for the four conditions are illustrated in figure 10.

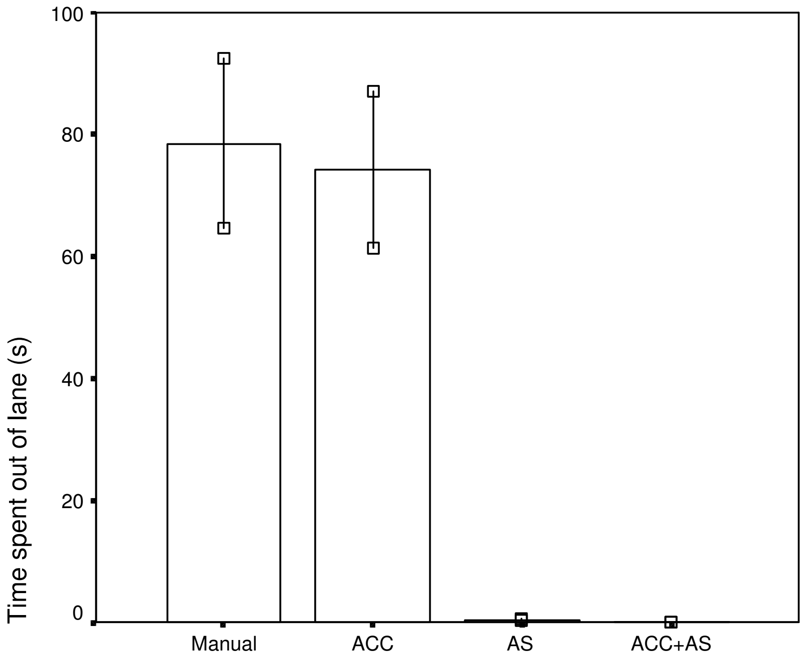

Figure 10. Time spent out of lane across automation conditions. Error bars represent one standard error

As in experiment 1, the lateral performance variables simply indicate that AS is better than the human at maintaining lane position. This result is less surprising in the current study, for which steering demands were relatively high, than in the previous experiment, when the only task was to keep the vehicle in a straight line. It should be borne in mind that the longitudinal demands were nontrivial in this study, yet the use of ACC did not improve participants' steering ability.

A main effect was observed for speed instability ($F_{3,30} = 2.96$, $p < 0.05$), however none of the specified contrasts reached significance. Post-hoc contrasts revealed that instability was significantly lower in the AS condition than it was in the ACC drive ($F_{1,10} = 9.41$, $p < 0.05$). Means for the four automation conditions are summarized in figure 11.

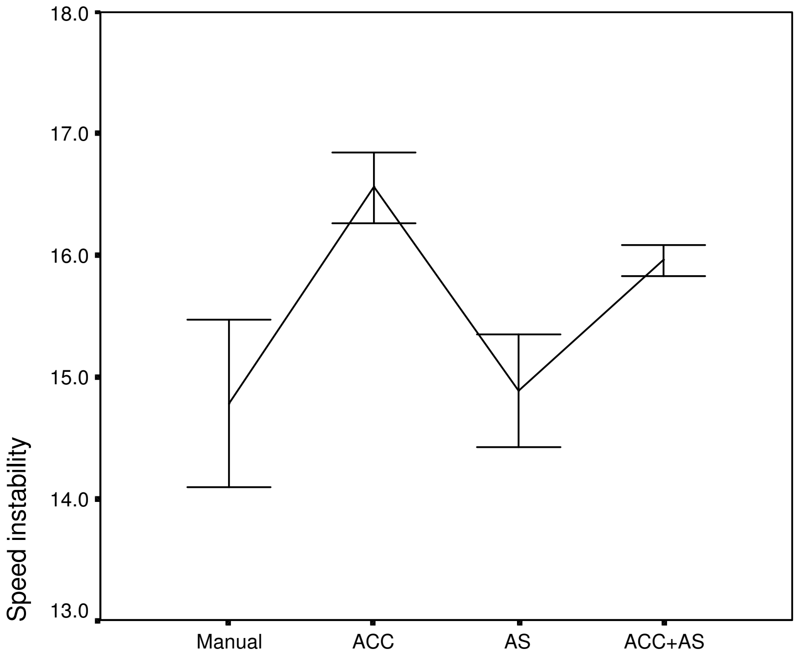

Figure 11. Speed instability across automation conditons. Error bars represent one standard error

A more pronounced effect was found for headway instability ($F_{3,24} = 6.14$, $p < 0.005$). This was due to reduced instability in the ACC ($F_{1,8} = 6.14$, $p < 0.05$) and ACC+AS conditions ($F_{1,8} = 12.6$, $p < 0.01$) compared to Manual driving. No difference was observed between the Manual and AS conditions. Mean instability statistics are presented in figure 12.

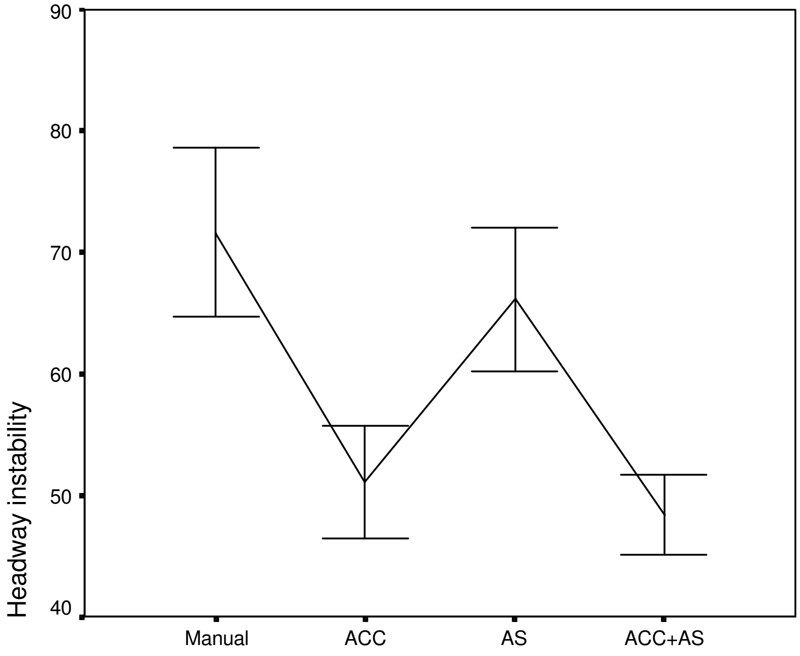

Figure 12. Headway instability across automation conditions. Error bars represent one standard error

It may seem confusing that ACC appeared to increase speed instability, although headway instability was improved. This apparent contradiction is readily explained, though, when the nature of the ACC system is considered. ACC was designed (in the simulator at least) to maintain set speed until a lead vehicle impeded progress. Once a lead vehicle was detected, speed was adjusted to match that of the target as closely as possible. Therefore, fluctuations in speed of the lead vehicle were almost exactly matched by the ACC car. In the present experiment, this feature served to maintain headway, but at the same time increased speed instability due to the oscillations between 48 kph (30 mph) and 112 kph (70 mph). Human control, on the other hand, dampened these speed oscillations by adopting a greater following distance. When the lead vehicle slowed down, it was not necessary to adjust speed a great deal, but distance headway was compromised. Such a driving style suggests that participants were economizing on their physical demands (i.e. repeatedly slowing down and speeding up) to create a smoother drive, but perhaps at the extent of increased headway monitoring demands.

3.2.2. Secondary task data. The number of correct responses on the secondary task was entered into a repeated measures ANOVA, with level of automation as the independent variable. As the purpose of the analysis was to determine reductions in MWL with levels of automation, repeated contrasts were used to determine the nature of any effects.

A significant main effect of automation was observed for the secondary task data ($F_{3,33} = 19.9$, $p < 0.001$). This was due a stepwise increase in responses across the automation conditions (Manual vs. ACC: $F_{1,11} = 7.38$, $p < 0.05$; ACC vs. AS: $F_{1,11} = 4.89$, $p < 0.05$; AS vs. ACC+AS: $F_{1,11} = 19.8$, $p < 0.005$). This pattern of responses differs from those found by Young and Stanton (2002) and in experiment 1 here, and fulfils the prediction made for the present study. Mean responses in each of the Manual, ACC, AS, and ACC+AS conditions are represented in figure 13.

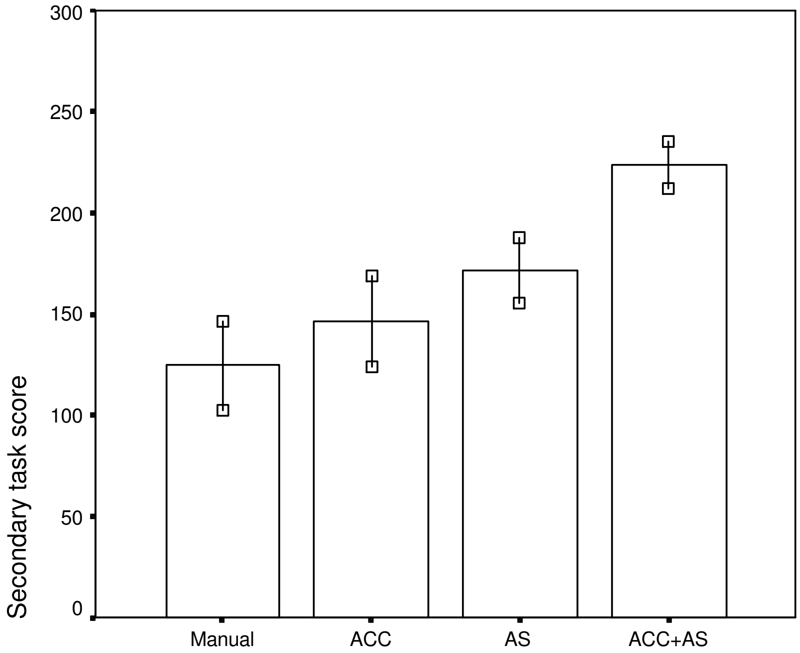

Figure 13. Secondary task scores across automation conditions. Error bars represent one standard error

With increased longitudinal demands, it is clear from these results that ACC can have a beneficial effect on spare attentional capacity. Therefore, whilst automaticity may dominate the task of maintaining a constant speed, following a variable-speed lead vehicle requires much more controlled processing. However, the steering demands of the present track layout are evidently still greater than those imposed by the following task. Nonetheless, the results show that Expert drivers can be relieved of attentional demands by ACC. The stepwise pattern for the secondary task score perfectly matches the prediction for this study.

3.2.3. Subjective data. As with the previous study, the NASA-TLX data were analyzed using repeated measures ANOVAs, with repeated contrasts to determine differences between adjacent conditions. Overall Workload was significantly affected by level of automation ($F_{3,33} = 43.5$, $p < 0.001$). Repeated contrasts revealed that the source of this effect was a significant decrease from Manual to ACC ($F_{1,11} = 9.61$, $p < 0.05$), and from AS to ACC+AS ($F_{1,11} = 89.0$, $p < 0.001$). The difference between ACC and AS was nonsignificant. Mean OWL scores in each condition are depicted in figure 14.

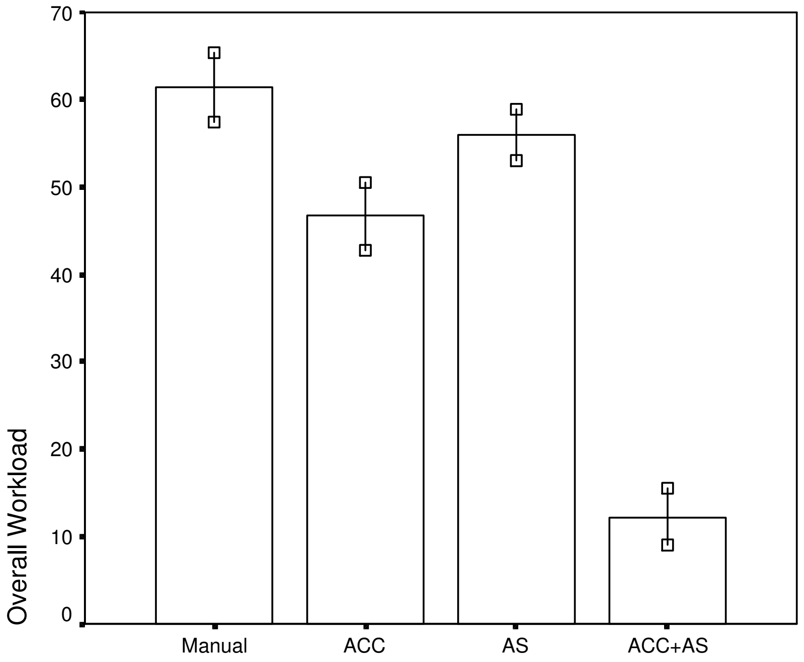

Figure 14. Overall Workload ratings across automation conditions. Error bars represent one standard error

Again, this pattern was not observed in any of the previous studies, and is consistent with the predictions made here. Rather than stepwise reductions in subjective MWL, though, it seems the new longitudinal task imposed similar levels of perceived demand as the steering task. The pattern of Overall Workload ratings further dissociates the subjective and secondary task measures of MWL, adding weight to the argument that subjective ratings are not sensitive to differences due to automaticity. Furthermore, the fact that the intermediate levels of automation are perceived as imposing equivalent levels of demand makes the present design much more balanced than that of Young and Stanton (2002). In other words, the longitudinal control task has been constructed to impose similar levels of subjective MWL as the steering task. This design would therefore be very useful for future studies.

In sum, the hypothesis that ACC would only reduce MWL when longitudinal demands were high was consistently supported by the results of this experiment. In particular, the predicted pattern of MWL was exactly matched by the secondary task data, and supported by the subjective data. Indeed, it could be argued that the perceived MWL results were better than expected, as the present design managed to achieve equivalence between longitudinal and lateral control demands. Therefore, it would seem that the task conditions as used in this study would be most appropriate for future studies.

One particularly notable finding from this study was the lack of a difference in lateral control performance between the Manual and ACC conditions. In spite of the decreased demands when driving with ACC, participants did not translate this into a performance improvement for their steering. This could represent a ceiling of performance for human lateral control, or it could be indicative of a MWL homeostasis effect, with participants adjusting their performance to maintain a consistent level of MWL (cf. Buck et al.1994, Zeitlin 1995).

Taking the results of experiments 1 and 2 together, it can be concluded that the more likely explanation for the findings of Young and Stanton (2002) was that the constant-speed task did not exploit the functionality of the ACC system. Although perceptions of demand may have been masked by the steering load, the level of automaticity achieved by Expert drivers in constant-speed driving meant that ACC could not relieve any attentional demands for that task. Forced variable-speed driving, on the other hand, is subject to controlled processing, providing the opportunity for ACC to relieve this element of driver MWL.

4. GENERAL DISCUSSION

4.1. Summary of results

Before going on to discuss the theoretical and practical implications of these two studies, a brief overview of the main results in each experiment is presented. Experiment 1 used a straight road to test the hypothesis that ACC may affect driver MWL when other demands are minimized. Experiment 2 took an alternative position, suggesting that ACC would relieve driver MWL if the longitudinal demands were increased, and employed a variable-speed lead vehicle to examine this assumption.

In both experiments, lateral control only exhibited a difference if steering was automated. Naturally, AS was better at maintaining lane position than the human driver, and humans drove further to the right (closer to the road centreline). Similarly, participants tended to drive more slowly and with longer headways than the ACC system. The instability scores, a judgemental measure of performance, were mostly equivalent across automation conditions if the task was to maintain constant speed on a straight road (experiment 1). The exception was a significant increase in the ACC+AS condition. This was probably due to data artifacts, such as collisions, despite the data being filtered prior to analysis. Under more demanding task conditions, the ACC system was significantly better at maintaining a constant headway from the variable-speed lead vehicle.

In experiment 1, driving on a straight road with ACC did not free any more additional resources than maintaining a constant speed manually. Participants did perceive a reduction in MWL on the TLX. This pattern now matches that for the Learners and Advanced drivers in Young and Stanton's (2004) experiment, implying that the extra steering demand in their design may indeed have masked the effect of ACC for the skill-based processing of Experts. However, the steering demand was obviously still quite substantial, as evidenced by the reduced MWL on both measures in the AS condition.

Driving on the original track with a variable-speed lead vehicle (Experiment 2) did affect spare capacity, in the stepwise fashion as predicted. Subjective MWL did not decrease in the same way, but most of the results were still consistent with the predictions. The Overall Workload scale did decrease with ACC, but there was no difference between ACC and AS. This does not refute the predictions, it simply means that the variable-speed task imposes similar levels of MWL as lateral control.

4.2. Implications: MWL and ACC

The results in these two related experiments support the idea that ACC can relieve the Expert driver of MWL, but only in cases where the traffic flow is variable. At a constant speed, processing of longitudinal control is fully automatic for Experts, and these drivers only perceive a benefit when other demands (i.e. steering) are minimized. Even in this case, though, objective demand (i.e. spare attentional capacity) does not increase over and above that when driving normally. Steering, being a second-order tracking task, is naturally more demanding than longitudinal control (Wickens et al. 1998), so AS reduces MWL even on a straight road.

From the applied viewpoint, these conclusions support the contention of vehicle manufacturers that ACC systems can offer added comfort and convenience to driving (Richardson et al. 1997). Indeed, the point of ACC is its adaptive nature, designed for the increased traffic density that is typical of roads in the UK. Standard CC devices are acceptable for highways in the USA, which tend to be long, straight, and relatively empty. However, British motorways are much busier, and speeds very often fluctuate due to traffic jams, accidents etc. Using CC would not provide any benefit in such an environment, and indeed may even increase workload and frustration, as it would be necessary to disengage and reengage the system continually. An ACC system, on the other hand, can cope with fluctuations in traffic flow, and thus leads to a reduction in MWL, as seen in experiment 2.

In addition to this applied conclusion, the results of this experiment indirectly support one of the early presumptions made in this paper: that new vehicle technologies will relieve driver load at a psychological level. Orthodox systems, such as CC, are not thought to relieve the driver of any mental workload, as there is little information processing involved in maintaining a constant speed. The results of this experiment indicate that this is indeed the case, at least as far as experienced drivers are concerned. One of the motivations of this research is based on concerns about the effects of future vehicle automation on driver MWL. In the light of the present conclusions, this motivation is well justified.

4.3. Implications: Experimental design

A general conclusion to emerge from the experiments conducted here and by Young and Stanton (2002, 2004) is that steering is a primary determinant of driver MWL. It is probably for this reason that no subjective workload differences were observed between Manual and ACC driving in the studies by Nilsson (1995) or Ward et al. (1995). The extra demands of steering simply mask the driver's perception of load. Objectively speaking, ACC does not actually relieve demand significantly unless the longitudinal demands are already high. Since ACC is essentially a coarse form of static automation, using it when actual demands are low will not significantly increase spare attentional capacity (indeed, in the constant-speed case, it is acting in a manner akin to conventional CC).

In terms of the most appropriate experimental design with which to assess the effects of ACC on driver performance, the conclusion here is to adopt the variable speed conditions of experiment 2. Only in this scenario are task demands actually reduced by ACC, as evidenced by the increased spare capacity. Furthermore, the results of experiment 2 were closely aligned with its predictions. This was not necessarily true for experiment 1, as the predictions for that study were only partially satisfied by its results. Finally, subjective MWL in the ACC and AS conditions were largely equivalent in experiment 2. From this it can be deduced that the perceived demands of longitudinal and lateral control were more evenly matched for those task conditions, whereas previously (in the absence of a substantial longitudinal task) steering imposed the predominant demands. Matching the demands of longitudinal and lateral control provides a superior experimental design, as automating each dimension has a similar effect on subjective MWL.

In sum, this experiment attempted to determine why ACC appeared not to have an effect on the MWL of Expert drivers in Young and Stanton's (2002) experiment. Findings from that study and the previous literature are in conflict about the effects of ACC on MWL. It was found that this conflict was mostly due to the task imposed by Young and Stanton (2001a). Simple car-following at a constant speed did not test the 'adaptiveness' of the ACC system, whereas following a variable speed vehicle exploited the full functionality of the device. However, there was also some evidence that effects of ACC on MWL may have been masked by the much greater demands of steering the vehicle. On the basis of the results presented here, it has been decided that future experiments investigating the effects of ACC on driver MWL should use a variable-speed lead vehicle.

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