Hysteresis in Mental Workload and Task Performance: The Influence of Demand Transitions and Task Prioritization

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Objective: We examine how transitions in task demand are manifested in mental workload and performance in a dual-task setting.

Background: Hysteresis has been defined as the ongoing influence of demand levels prior to a demand transition. Authors of previous studies predominantly examined hysteretic effects in terms of performance. However, little is known about the temporal development of hysteresis in mental workload.

Method: A simulated driving task was combined with an auditory memory task. Participants were instructed to prioritize driving or to prioritize both tasks equally. Three experimental conditions with low, high, and low task demands were constructed by manipulating the frequency of lane changing. Multiple measures of subjective mental workload were taken during experimental conditions.

Results: Contrary to our prediction, no hysteretic effects were found after the high- to low-demand transition. However, a hysteretic effect in mental workload was found within the high-demand condition, which degraded toward the end of the high condition. Priority instructions were not reflected in performance.

Conclusion: Online assessment of both performance and mental workload demonstrates the transient nature of hysteretic effects. An explanation for the observed hysteretic effect in mental workload is offered in terms of effort regulation.

Application: An informed arrival at the scene is important in safety operations, but peaks in mental workload should be avoided to prevent buildup of fatigue. Therefore, communication technologies should incorporate the historical profile of task demand.

Keywords: hysteresis, demand transitions, mental workload, effort regulation, driving simulation, task prioritization

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HUMAN FACTORS
Vol. XX, No. X, Month XXXX, pp. 1–15
DOI: 10.1177/0018720816669271

INTRODUCTION

> After a short break at the police station, C. and S. return to their surveillance duty. The dispatcher calls: “A missing girl possibly showed up at relatives and should be picked up.” While S. tries to write down the address in his notebook, they realize they missed the girl’s full name and the house number. S. feels stupid for having to ask again. Directly afterwards an alarm goes off. S. glances at the mobile data terminal: “It’s a white vehicle with an unpaid fine.” C. looks around, locates the car, and immediately makes a turn. Just as S. tries to request information on the driver, the dispatcher interrupts him: “We are detaching you from the previous call. Someone has been spotted in a building that burned down last week.” C. recognizes the address, turns the car again, and accelerates. On their way, S. declines another alarm with a lower priority. They arrive at the scene only minutes later, to find a man in ragged clothes carrying a bag full of copper. (field notes from Jansen, van Egmond, de Ridder, & Silvester, 2014, p. 15)

This anecdote illustrates how police officers continuously perform in-vehicle tasks while driving, such as memorizing incoming radio messages, verbal communication, and operating the mobile data terminal (Anderson, Courtney, Plecas, & Chamberlin, 2005; Jansen et al., 2014). It also makes clear that, unlike regular traffic participants, police officers do not have the choice to ignore incoming messages. Within this multitask context, police officers are engaged in a variety of activities with different levels of task demand. For example, rushing to catch a thief likely imposes a greater driving task demand than transporting said thief to the police station, because the former activity requires driving at a higher speed while avoiding other traffic. Police work is also characterized by a perpetual switching between activities (Borglund & Nuldén, 2012; Jansen et al., 2014; Sørensen & Pica, 2005), leading to frequent and sudden transitions between high and low task demands.

The absolute demand level prior to a sudden demand transition is known to affect performance and mental workload for a certain period directly after such transition occurs (for overviews, see Cox-Fuenzalida, 2007; Morgan & Hancock, 2011). This ongoing influence of prior demand level is referred to as *hysteresis* (Cumming & Croft, 1973; Farrell, 1999; Goldberg & Stewart, 1980; Morgan & Hancock, 2011). Previous studies have shown that hysteresis degrades over time in terms of performance (Gluckman, Warm, Dember, & Rosa, 1993; Matthews, 1986). However, surprisingly little is known about how this temporal nature of hysteresis affects concomitant mental workload.

Our present study focuses on how hysteresis after demand transitions evolves over time, both in terms of performance and mental workload. In line with the above police example, a driving task was combined with an auditory memory task. Demand transitions were induced by manipulating the difficulty of the driving task while keeping the auditory memory task at the same demand level. In addition, task prioritization was manipulated between participant groups to reflect the constraint that police officers do not have the choice to ignore incoming messages, whereas regular drivers do. This study informs an understanding of existing theories on hysteresis (i.e., resource depletion, effort regulation) by assessing mental workload not only after but also during ongoing experimental performance.

Hysteresis in Performance

Authors of several studies have described how hysteresis develops over time by comparing multiple periods of aggregated performance data (Matthews, 1986; Gluckman et al., 1993; Ungar et al., 2005; Cox-Fuenzalida, 2007). Matthews (1986) aggregated performance on a visual signal detection task in 15 consecutive periods of 10 s each. Task demand was manipulated by varying the number of co-occurring stimuli. A sudden transition from high to low task demand resulted in an immediate performance reduction that lasted for six periods (i.e., 1 min in total), before returning to a performance level similar to that of a low-task-demand control group. Gluckman et al. (1993) aggregated performance over a longer period but at a lower temporal resolution. Demand transitions were induced by shifting from two parallel visual signal detection tasks to one signal detection task or vice versa. Pretransition and posttransition performance was measured in two periods of 10 min and compared against nonshifting control groups. A hysteresis effect in the form of lower performance was found only with the shift from dual task to single task. This effect was found in the first period of 10 min after the demand transition but not in the second period.

The aforementioned studies demonstrate that hysteresis in performance decays over time. Two other studies, however, indicate that sudden demand transitions can have permanent hysteretic effects. Ungar et al. (2005) induced a demand transition by shifting from a compensatory tracking task with a visual signal detection task to the compensatory tracking task only. The resulting hysteretic effect persisted throughout all posttransition periods (i.e., 8 × 2 min). Cox-Fuenzalida (2007) manipulated the difficulty of an auditory signal detection task and also found a hysteretic effect that persisted throughout all posttransition periods (i.e., 3 × 3 min). Although in these studies hysteresis seems to be permanent, it should be noted that different experimental tasks and modalities were used, as compared with those by Matthews (1986) and Gluckman et al. (1993). It is still possible that the experimental conditions in Ungar et al. and Cox-Fuenzalida were too short to measure any existing decay in hysteresis. Regardless, these studies show that the partitioning of performance data into a sequence of posttransition periods is essential to investigate how hysteresis develops during the time frame of an experimental condition and thus potentially in real-world situations.

Gluckman et al. (1993) interpreted the finite duration of hysteresis, and the fact that hysteresis occurred only at a transition to lower demands, in terms of two theories: *resource depletion* and *effort regulation*. The resource depletion theory is an analogy to the recovery of muscle tissue in exercise physiology (Cannon, 1932). The high demands of dual tasking may have caused a resource debt, which could be satisfied through temporary regeneration after a transition to a lower demand. Alternatively, the findings were explained in terms of an effort regulation theory (see Hancock & Warm, 1989), in which increased mental effort is viewed as a means of regulating resources under varying demands (Hockey, 1997). Initial dual tasking may have formed a policy to distribute resources across the two interfering tasks. If this resource allocation policy is maintained after the transition to the single task, then the remaining task receives suboptimal resource allocation. Continued single-task exposure led to a revision of policy. In other words, the resource depletion theory interprets hysteresis in terms of recuperation, whereas the effort regulation theory interprets hysteresis in terms of strategic persistence. A next question, then, is whether hysteresis also degrades over time in terms of mental workload.

Hysteresis in Mental Workload

Three studies on demand transitions have assessed mental workload in addition to performance. In the first of these, Hancock, Williams, and Manning (1995) subjected participants to three trials on a compensatory tracking task. The first and the third trials were performed at an identical difficulty level. When the second trial was set to a lower difficulty level, mental workload (i.e., NASA Task Load Index [NASA-TLX] and Subjective Workload Assessment Technique [SWAT] ratings) in the third trial increased compared with the first trial. Conversely, when the second trial was set to a higher difficulty level, mental workload in the third trial was rated lower than the first trial. Matthews and Desmond (2002) induced a demand transition by shifting from a dual-task driving trial (i.e., with a signal detection task) to a single-task driving trial. Shifted drivers reported higher mental workload on the NASA-TLX than nonshifted drivers. Furthermore, shifted drivers showed impaired driving performance on straight road sections in the single task but not on curvilinear road sections. Morgan and Hancock (2011) also used a driving setting. Task demand was temporarily increased with a problem-solving task halfway through the drive. The problem-solving task increased mental workload on the simplified SWAT (S-SWAT) compared with a baseline measure, and this increase persisted until the end of the drive. The mental effort component of the S-SWAT proved to be the only contributor to this hysteresis. The effect was attributed to short-term memory overload (cf. Reid & Nygren, 1988), akin to the resource depletion theory (Gluckman et al., 1993).

The aforementioned three studies demonstrate that hysteresis is also manifested in mental workload. However, none of them partitioned the data in a sequence of posttransition periods, because subjective workload ratings were collected only once after each experimental condition. Consequently, the development of mental workload during experimental conditions could not be investigated. Moreover, the hysteretic effects may have lasted longer than the duration of an experimental condition (i.e., 2 to 5 min).

Frequent online ratings of subjective mental workload appear to solve the aforementioned problem. One concern with online ratings, however, is that they may be intrusive to the experimental tasks. A study by Hill et al. (1992) suggested that intrusiveness can be minimized with unidimensional rating scales as opposed to multidimensional rating scales (e.g., NASA-TLX, SWAT). However, this strategy comes at the expense of reduced diagnosticity. Morgan and Hancock (2011) showed why high diagnosticity is important for the interpretation of hysteresis in mental workload. An appropriate balance between low intrusiveness and high diagnosticity may be obtained by combining an online unidimensional scale with a multidimensional scale at the end of each experimental condition, whereby the latter scale is used to interpret the former. Such an effort is thus enacted here.

Paradigm

In the present study we examine hysteresis in a dual-task setting with a continuous driving task and a continuous auditory memory task, inspired by operational policing (Jansen et al., 2014). Driving task demand was manipulated by increasing the frequency of lane-changing maneuvers. This manipulation resulted in three experimental dual-task conditions with a low-high-low demand schedule. Hysteretic effects were tested by comparing driving performance, memory performance, and mental workload across the conditions with low demands (cf. Hancock et al., 1995).

The unidimensional Instantaneous Self Assessment (ISA) scale (Jordan, 1992; Leggatt, 2005; Tattersall & Foord, 1996) was used to assess mental workload during experimental conditions. The ISA scale was initially developed for the aviation context, but recent studies have shown that it is also sensitive to variations in traffic conditions (Girard, Wilczyk, Barloy, Simon, & Popieul, 2005) and to the distraction of a memory task while driving (Lemercier et al., 2014). The original ISA protocol uses a visual signal to prompt participants to rate their experienced workload level on a keypad. To minimize interference with the visual/manual driving task, we adapted this protocol by using an auditory trigger and by eliciting verbal numeric responses. ISA prompts did not co-occur with auditory memory items to minimize interference with the memory task. In addition to the ISA ratings, the NASA-TLX (Hart & Staveland, 1988) was administered at the end of each experimental condition. NASA-TLX subscales (i.e., mental demand, physical demand, temporal demand, subjective performance, effort, frustration) were used to interpret ISA ratings collected during the experimental conditions.

Although radio communication is viewed as a distraction and a risk for all drivers (Caird, Willness, Steel, & Scialfa, 2008; Dressel & Atchley, 2008), police officers do not have the choice to ignore incoming messages. As a result, police officers frequently have to deprioritize the driving task in favor of secondary tasks, especially in case of solo patrols. We addressed this difference in task prioritization through separate instructions for solo patrols (i.e., *equal instruction*) and regular driving (i.e., *driving instruction*).

The manipulation of task prioritization could provide an alternative paradigm to test the theories proposed by Gluckman et al. (1993). The effort regulation theory can be tested with the driving instruction, which should result in a protection of driving at the cost of memory performance. Thus, memory performance should decrease as the driving task becomes more demanding. The effort regulation theory predicts a temporary persistence of this resource allocation policy. A sudden decrease in driving demand should then result in impaired memory performance but not in impaired driving performance. The resource depletion theory, on the other hand, can be tested through a comparison between the instructions. The equal instruction is likely to confront drivers with higher overall demands than the driving instruction (Jansen, van Egmond, & de Ridder, 2016; Kantowitz & Knight, 1976; Norman & Bobrow, 1975). The higher the resulting resource debt, the longer one can expect recuperation to last after a high- to low-demand transition. Therefore, the resource depletion theory predicts a longer hysteretic effect with the equal instruction set.

METHOD

Participants

Twenty-eight students from the Department of Psychology at the University of Central Florida (UCF) were recruited to participate in the experiment. There were 10 males and 18 females, ranging in age from 18 to 41 years old ($M = 19.9$ years, $SD = 4.4$). They were compensated for their time with class credit. The study was approved by UCF's ethical committee. Participants had normal or corrected-to-normal vision. All participants had a current driver's license ($M = 3.4$ years, $SD = 4.0$), and on average they drove 179 km (111 miles) per week ($SD = 205$ km, 127 miles).

Auditory Memory Task

An initial set of 98 auditory stimuli was compiled, consisting of American radio news items spoken by professional newsreaders (*Here and Now*, http://hereandnow.wbur.org/section/radio). Selected news items were at least 1.5 years old to minimize recency effects. A native speaker from the United States recorded a factual question for each news item. Questions were related to numbers or names close to the

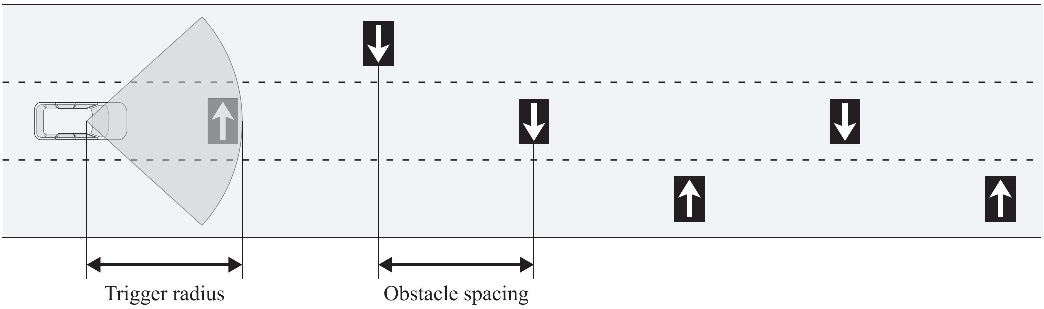

Figure 1. Track layout with obstacles. The displayed ratio between trigger radius and obstacle spacing corresponds with the "easy" obstacle map.

center of each news item and allowed for only one correct answer. For example, we presented the following item:

> Mixing chemicals in a high school lab is challenging enough. Now imagine you are doing it blind. A group of visually impaired students from all over the country had that chance at Metro State University in Denver recently, as part of an effort to get more blind people interested in science, technology, and math.

This item was accompanied by the question, "In which city was the university located?" The news items and questions were normalized to the same average volume and were saved as wav files (16 bit, 44.1 kHz).

In an initial pilot procedure with 15 participants, each item plus its accompanying question was presented to five participants. Questions that were answered incorrectly by more than 75% of these participants were removed. The final auditory stimulus set consisted of 64 news items ($M = 17.2$ s, $SD = 1.20$ s). Sixteen of these were used for training, whereas the other 48 were used in three experimental conditions. The goal of the memory task was to correctly answer a question for each stimulus.

Driving Task

The goal of the driving task was to avoid obstacles on a roadway without speeding. A simulated driving environment was created by placing obstacles on a straight, 8.5-km (5.3-mile) section of a simulated three-lane freeway. No additional traffic was added to these scenarios. The straight section could not be finished within the duration of any one experimental condition if the driver followed the posted speed limit of 56 km/h (35 mph).

In terms of spatial distribution, the first obstacle and ensuing odd obstacles were positioned on the center lane (see Figure 1). The other interpolated obstacles were pseudorandomly distributed in the two outer lanes. The obstacles were composed of flashing arrow signs that required the driver to change lanes. Arrows pointed rightward when positioned on the left lane and vice versa. In the center lane, the arrows pointed in the direction of the next obstacle (i.e., either left or right).

The first obstacle was positioned at 0.3 km (0.19 miles) into the drive. Subsequent obstacles were equally distributed over the remaining freeway section. Three obstacle maps were created, which differed in the longitudinal distribution of the obstacles. $\text{MAP}_{\text{training}}$ had an obstacle spacing of 100 m (328 ft). In MAP_{far} and MAP_{near}, the obstacle spacings were 150 m (492 ft) and 82 m (269 ft), respectively. Additionally, the obstacle trigger radius was varied across map conditions. The driver could see two obstacles ahead in $\text{MAP}_{\text{training}}$, due to a trigger radius of 200 m (656 ft). In MAP_{far}, the next obstacle appeared as the driver passed an obstacle (trigger radius: 148 m, 486 ft), whereas obstacles appeared relatively suddenly in MAP_{near} (trigger radius: 50 m, 164 ft). Although hitting obstacles did not affect driving speed, the instruction set explicitly required drivers to avoid all obstacles and to answer all memory questions correctly.

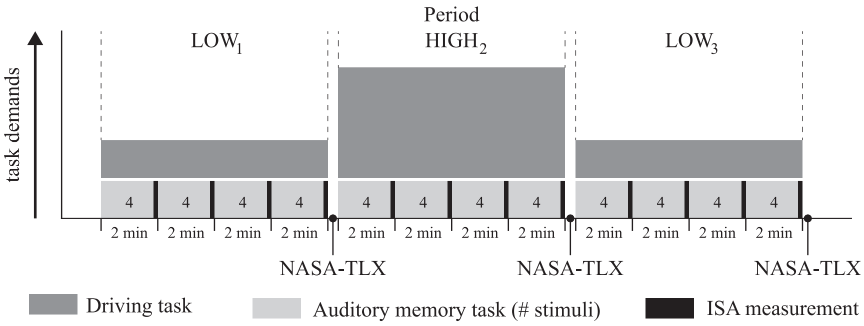

Figure 2. Task demands as function of the experimental conditions LOW_1, $HIGH_2$, and LOW_3.

Experimental Design and Measures

A mixed design was used, with driving task demand as repeated factor and priority instruction as between-subjects factor. The driving instruction was to prioritize the driving task over the memory task, whereas the equal instruction required the driver to perform both tasks as well as possible. Driving task demands were manipulated through a combination of obstacle spacing and trigger radius. Three experimental conditions were used with a fixed order: LOW_1, $HIGH_2$, and LOW_3 (see Figure 2). MAP_{far} and the corresponding trigger radius were used in the LOW_1 and LOW_3 conditions. MAP_{near} was used in the $HIGH_2$ condition. Memory task demand was not changed across driving conditions. Hysteresis was examined by comparing performance and mental workload in LOW_3 with LOW_1.

Two measures of mental workload were taken, namely, NASA-TLX and ISA. The NASA-TLX was administered after each condition. Furthermore, the memory task was interleaved with ISA prompts, which followed after each block of four memory trials (see Figure 2). ISA mental workload ratings were collected verbally. A pilot study suggested that a 5-point scale was insufficiently sensitive to discern between the high and low levels of driving task difficulty. Therefore, a 7-point scale was used, where 1 corresponded with a *very easy task* and 7 with a *very difficult task*. Driving performance and memory performance were calculated over two time frames: per period (8 min each) and per 2-min trial block (i.e., four memory trials with an ISA prompt). Driving performance was measured in terms of absolute velocity as well as the root mean square error (RMSE) of the velocity. Memory performance was measured as the proportion of correct answers. These proportions were transformed via an arcsine transformation (Zar, 1996, p. 282) for subsequent statistical analyses. All statistical tests were conducted with SPSS v22, and results were tested using an alpha level of .05.

Apparatus

A fixed-platform police training simulator was used (L3 STS, Inc.). The simulator featured a cab complete with steering wheel and dashboard from an actual automatic transmission vehicle. Three 52-in. screens (1,024 × 768 pixels at 60 Hz) mounted at a distance of approximately 1.0 m from the driver provided a 120° view of the driving environment (and see Morgan & Hancock, 2011). Driving speed was sampled at 60 Hz. The NASA-TLX was administered via Qualtrics.com, presented on a tablet next to the simulator. A dedicated program, coded in Max v.6 (Cycling74, Inc.), was used to play prerecorded instructions, to randomize stimuli for each participant, to collect demographic information, and to record verbal responses to memory trials and ISA prompts through an external microphone. Sounds were played back over a pair of Altec Lansing AVS200 computer speakers positioned on the dashboard. Auditory stimuli were presented at a comfortable listening level, clearly audible above the simulator sounds. Collection of driving performance measures and trigger behavior was handled through custom software (see Sawyer & Hancock, 2012).

Experimental Procedure

Participants were randomly assigned to either the driving instruction (*n* = 14) or the equal instruction (*n* = 14). Each session was organized in three phases: training, experimentation, and interview. Upon arrival, participants were asked to complete the informed consent and to turn off all electronic devices. Each participant was then trained in the memory task and in responding to ISA trials (i.e., "Report how much mental workload the task just required"). Memory trials were composed of a news item (*M* = 17.2 s, *SD* = 1.2 s), 1.0 s silence, a question (*M* = 2.6 s, *SD* = .6), 4.5 s answer time, a beep sound, and 2.0 s silence. After every fourth memory trial, an ISA trial was triggered in order to obtain a mental workload rating. Such trials started with a chicken "squawk," a salient prompt to attract attention, then provided 7.0 s answer time, a beep sound, and 2.0 s silence. Participants were trained to verbalize an answer during the designated interval. Answering after the beep sounds of the memory trials and ISA prompts was permitted, but the participant was urged to prepare for the next trial. Four minutes of single-task practice followed, consisting of eight memory trials, presented in random order, and interleaved by two ISA prompts.

Dual-task training took place in the driving simulator, using the $\text{MAP}_{\text{training}}$ condition. Participants were instructed to shift lanes according to the direction of the arrows and to maintain driving speed at or below 35 mph (56 km/h). A driving or an equal-priority instruction was given, depending on the allocated group. Regardless of the instruction, each participant was directed to provide a rating related to the combination of both tasks in response to ISA prompts. The first memory trial was triggered directly after the participant had passed the fourth obstacle (i.e., after approximately 1 min). The timing of subsequent memory trials, ISA prompts, and obstacles, was not synchronized. As with the memory training, two ISA prompts took place amid eight memory trials (i.e., 4 min in total). The remaining training stimuli were used. Upon completion, the participant was instructed to stop and turn off the vehicle. Demographic information was obtained afterward.

The experimental condition LOW_1 employed the same instructions as dual-task training. However, the first memory trial was already triggered as the second obstacle became visible. Sixteen memory trials and four ISA prompts were presented, with a total duration of 8 min. The auditory tracks were pseudorandomly selected from a pool of 48 experimental tracks, such that between participants the stimuli were counterbalanced over the three experimental conditions. Furthermore, each block of four memory trials had a similar distribution of number- and name-related questions. The participant completed a NASA-TLX questionnaire after turning off the vehicle. The experimental conditions HIGH_2 and LOW_3 started as soon as the NASA-TLX of the previous condition had been completed. The remaining stimuli were presented according to the aforementioned protocol. The priority instruction was repeated before each condition. Sessions ended with open questions about the overall dual-task experience during the experiment, what strategy was used, how it felt to act according to a priority instruction, recognition of news items, and news-listening habits.

RESULTS

Five participants were excluded from further analysis. Three of these finished the track before the memory task was completed. One participant was excluded due to technical issues with the simulator. Finally, one participant left the simulator to make a phone call. As a result, 23 participants (driving, *n* = 11, equal, *n* = 12) were included in the present analysis. All of them responded to all ISA prompts in the experimental conditions. The driving task was performed as instructed, in that no obstacles were hit. The only exception was one driver who hit one obstacle out of 186 obstacles passed. Demand transitions were first analyzed at the time frame of a full experimental condition, so that the diagnostic power of the NASA-TLX can be used to interpret ISA ratings. This analysis was followed by an analysis at a trial block time frame. Manipulation checks of task difficulty and priority instructions were performed, using the same temporal distinction between full experimental conditions and trial blocks, due to an apparent absence of evident hysteresis. Finally, the impact of task prioritization is investigated.

Demand Transitions Between Experimental Conditions

The average duration of the transition from LOW_1 to HIGH_2 was 149.48 s ($SE = 7.42$). This duration was measured from the end of the last ISA prompt in LOW_1 to the start of the first memory trial in HIGH_2. The second transition from HIGH_2 to LOW_3 ($M = 106.26$ s, $SE = 4.23$) took significantly less time, $F(1, 21) = 33.32$, $p < .001$, $\eta^2_p = .61$. This finding perhaps indicates a learning effect with respect to completing the NASA-TLX.

If demand transitions induced hysteresis, then performance and/or mental workload after HIGH_2 should differ from before HIGH_2. Panels A, C, E, and G in Figure 3 show that task performance and ISA ratings were similar in both LOW_3 and LOW_1, regardless of the instruction. Mixed 2 (instruction) × 2 (period) ANOVAs confirmed these observations, such that no significant effects were found. Although the average NASA-TLX ratings (Figure 4A) are similar in the LOW_1 and LOW_3 conditions, the driving instruction appears to show differences on the subscales Physical Demand (Figure 4C), Temporal Demand (Figure 4D), and Frustration (Figure 4G). Within the equal instruction, effort (Figure 4.F) appears lower in LOW_3. However, a mixed 2 (instruction) × 2 (period) × 6 (NASA-TLX scales) MANOVA yielded no significant effect. These findings imply that if demand transitions caused hysteresis, then the duration of such hysteresis must be shorter than the full experimental duration (i.e., 8 min).

Demand Transitions Between Trial Blocks

If no effect can be established across an extended interval of time, the next question is whether such an effect is potentially more transient in nature. To examine this question, we use trial blocks (i.e., four memory trials plus an ISA prompt) that serve to offer a higher temporal resolution to identify hysteresis in terms of both performance and workload. The right panels in Figure 3 show task performance and ISA ratings per trial block. No NASA-TLX ratings were obtained at this resolution. Therefore, linear regressions were run to evaluate how ISA ratings related to the unweighted average of the six NASA-TLX subscales. ISA variance was significantly explained by TLX in LOW_3, $F(1, 21) = 4.86$, $p < .05$, $R^2 = .19$; $\beta_{\text{std}} = .43$, $t(22) = 2.21$, $p < .05$, but not in the other experimental conditions. The latter suggests that ISA ratings should not be interpreted in terms of overall workload. Multiple linear regressions were run to investigate whether the subscales could explain the ISA ratings. The stepwise method excluded five subscales in each experimental condition. In HIGH_2, the variance of ISA was significantly explained by effort, $F(1, 21) = 6.25$, $p < .05$, $R^2 = .23$; $\beta_{\text{std}} = .48$, $t(22) = 2.50$, $p < .05$. Furthermore, mental demand explained a significant amount of ISA variance in the LOW_1, $F(1, 21) = 6.98$, $p < .05$, $R^2 = .25$, and LOW_3, $F(1, 21) = 7.31$, $p < .05$, $R^2 = .26$, conditions. The analyses showed that mental demand significantly predicts ISA ratings in LOW_1, $\beta_{\text{std}} = .50$, $t(22) = 2.64$, $p < .05$, and in LOW_3, $\beta_{\text{std}} = .51$, $t(22) = 2.70$, $p < .05$. These findings indicate that ISA ratings during LOW_1 and LOW_3 can be interpreted in terms of mental demand.

The shortest time frame to identify hysteresis can be established by comparing the last trial block of LOW_1 (i.e., Block 4) with the first trial block of LOW_3 (i.e., Block 9). Participants with the driving instruction showed decreasing driving speeds from Block 4 to Block 9 (Figure 3B) as well as increasing memory performance (Figure 3F) with decreasing ISA ratings (Figure 3H). Conversely, participants with the equal instruction showed increasing driving speed, decreasing memory performance, and increasing ISA ratings. However, neither of these interactions between block and instruction proved to be significant at this juncture. RMSE of driving speed (Figure 3D) appears stable from Block 4 to Block 9, which was confirmed through statistical analysis. The only significant effect was found on ISA ratings. Participants with the equal instruction reported higher mental workload than participants with the driving instruction, $F(1, 21) = 5.21$, $p < .05$, $\eta^2_p = .20$. However, this finding was not related to hysteresis per se. To summarize, no hysteretic effects were distinguished at a trial block time frame.

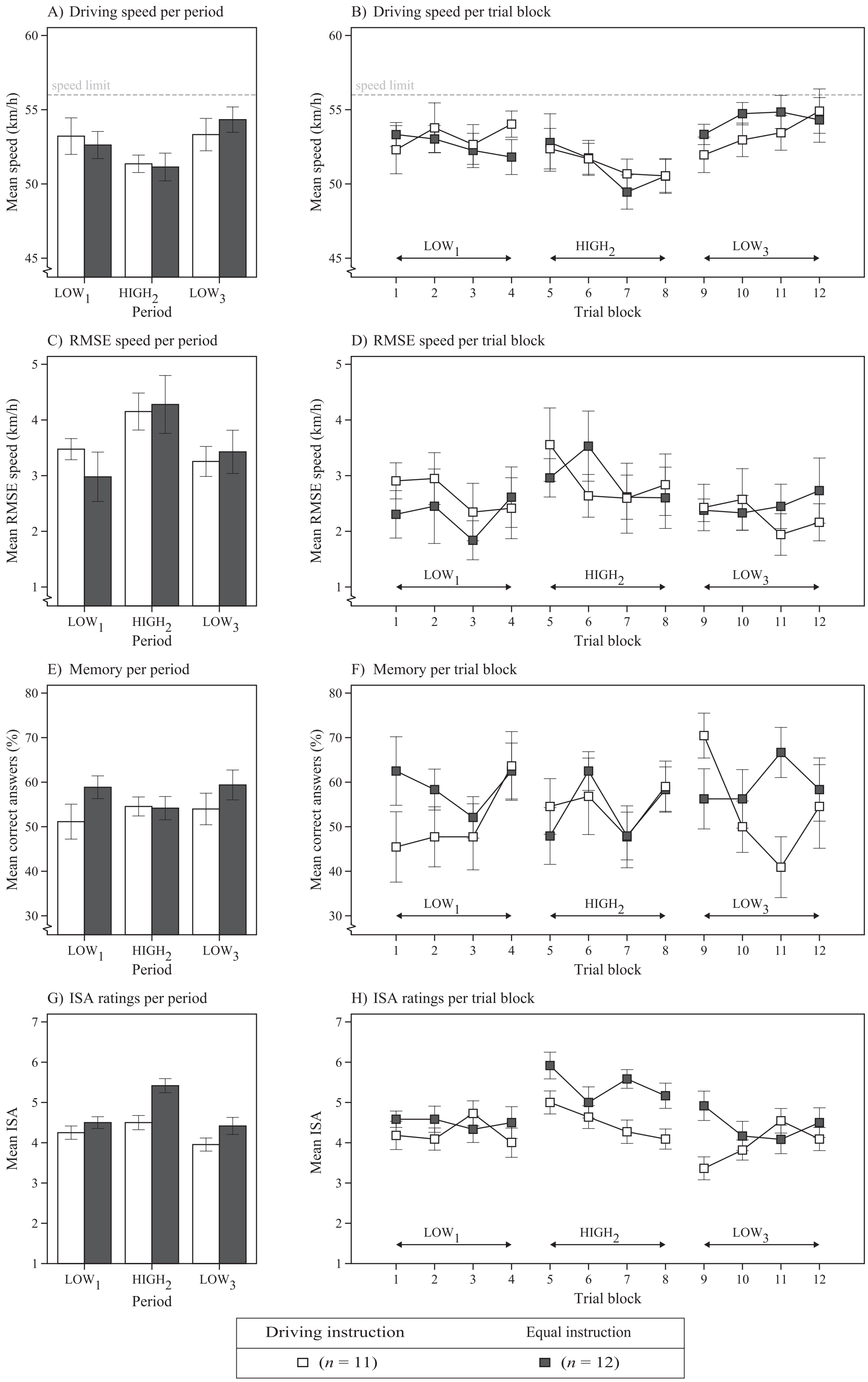

Figure 3. Task performance and workload as function of priority instruction. Error bars represent ±1 standard error of the mean, corrected for within-subjects variability. Root mean square error of driving speed is higher per period than per trial block because it is calculated over a longer time frame.

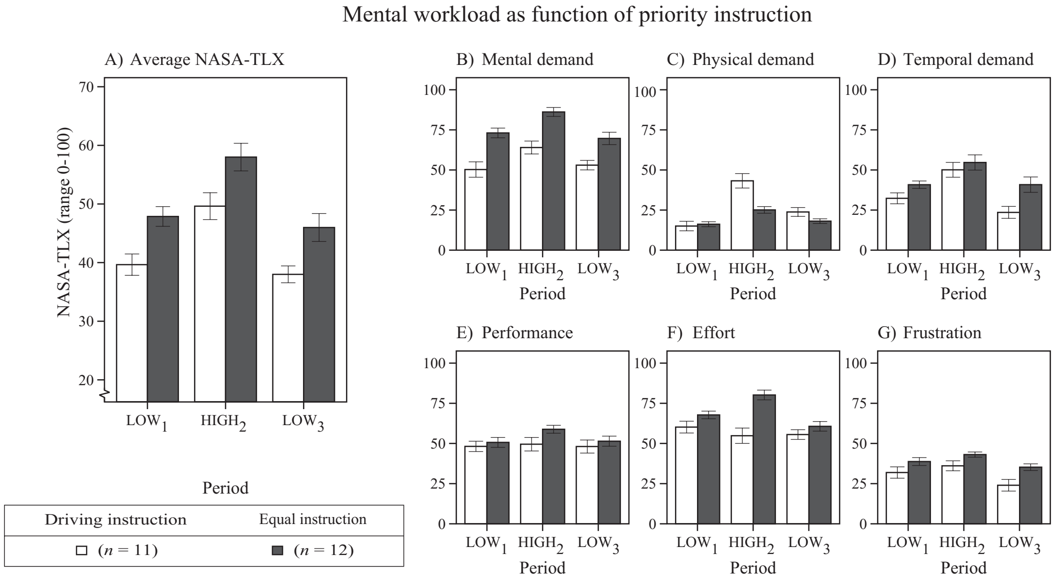

Figure 4. Unweighted average NASA Task Load Index (NASA-TLX) and NASA-TLX subscales as function of priority instruction. Error bars represent ±1 standard error of the mean, corrected for within-subjects variability.

Manipulation Check of Experimental Conditions

The absence of hysteresis raises the question whether the prerequisites to identify such effects were met. Most importantly, the manipulation of driving task difficulty should be reflected in task performance and/or mental workload. A 3 (period) × 2 (instruction) mixed ANOVA did not yield significant effects on task performance. However, a significant effect of period on ISA ratings was found, $F(2, 42) = 7.09, p < .01, \eta^2_p = .25$. ISA ratings increased significantly from LOW_1 to HIGH_2, $F(1, 21) = 9.29$, $p < .01$, $\eta^2_p = .31$, and decreased from HIGH_2 to LOW_3, $F(1, 21) = 10.77$, $p < .01$, $\eta^2_p = .34$ (see Figure 3G).

Figure 4A shows that the unweighted NASA-TLX average increased from LOW_1 to HIGH_2 and then subsequently decreased from HIGH_2 to LOW_3. Furthermore, the equal instruction appears to induce greater mental workload than the driving instruction. Panels B through G in Figure 4 suggest that the dual-task combination induced considerable mental demand and effort but not so much physical demand or frustration. Multivariate results of a 3 × 2 × 6 MANOVA yielded a significant main effect of period, Wilks's lambda = .37, $F(12, 74) = 3.95, p < .001$, $\eta^2_p = .39$, and a significant interaction between period and instruction, Wilks's lambda = .55, $F(12, 74) = 2.18$, $p < .05$, $\eta^2_p = .26$. No significant main effect of instruction was found, however.

Univariate ANOVAs showed that the main effect of period was significant on four subscales (see Table 1): Mental Demand, Physical Demand, Temporal Demand, and Frustration. Contrast analyses revealed a significant increase from LOW_1 to HIGH_2 and a significant decrease from HIGH_2 to LOW_3 for mental demand, physical demand, and temporal demand. Frustration increased significantly only from LOW_1 to HIGH_2. The interaction between period and instruction was significant for physical demand and effort. Physical demand increased from LOW_1 to HIGH_2, but this increase proved to be larger in the driving instruction (see Figure 4C). Effort decreased from HIGH_2 to LOW_3 but only in the equal instruction group (see Figure 4F). To summarize, across the time frame represented by an experimental condition, the manipulations of driving task difficulty and priority instruction proved to be reflected in mental workload. However, no effects were found on task performance.

TABLE 1: Results of Univariate ANOVAs on the NASA-TLX Subscales

		Univariate ANOVA			Contrast Analysis (Type: Repeated)				
NASA-TLX Subscale	Source	*df*	*F*	η^2_p	*df*	*F*	η^2_p	*F*	η^2_p
Mental Demand	P	(2, 42)	6.26**	.23	(1, 21)	8.56**	.29	11.77**	.36
Physical Demand	P	(1.45, 30.37)	16.89***	.45	(1, 21)	23.52***	.53	12.80**	.38
Temporal Demand	P	(1.59, 33.33)	9.18**	.30	(1, 21)	12.03**	.36	11.06**	.35
Frustration	P	(2, 42)	4.30*	.17	(1, 21)	*Ns*	—	10.19**	.33
Physical Demand	P × I	(1.45, 30.37)	4.42*	.17	(1, 21)	6.35*	.23	*ns*	—
Effort	P × I	(2, 42)	3.61*	.15	(1, 21)	*ns*	—	5.13*	.20

Note. TLX = Task Load Index; P = period; I = instruction. Only significant effects are reported. The degrees of freedom of physical demand and temporal demand were adjusted using Greenhouse-Geisser, $\varepsilon = .72$ and $\varepsilon = .79$, respectively.
*$p < .05$. **$p < .01$. ***$p < .001$.

Manipulation Check of Trial Blocks

Although the previous manipulation check was appropriate for the time frame of an experimental condition, it is insufficiently discriminative for shorter durations. The right panels of Figure 3 show detailed patterns of task performance and ISA ratings at the resolution of a trial block. The manipulation of driving task difficulty should be visible in the first transition from LOW$_1$ to HIGH$_2$ (i.e., Trial Block 4 vs. 5) and the second transition from HIGH$_2$ to LOW$_3$ (i.e., Trial Block 8 vs. 9). However, 2 (block) × 2 (instruction) mixed ANOVAs on each transition did not yield significant effects for task performance. The only significant effect was found in the first transition of the ISA ratings (Figure 3H), which increased from Trial Block 4 to Trial Block 5, $F(1, 21) = 8.10$, $p < .05$, $\eta^2_p = .28$.

Surprisingly, no significant effects on ISA ratings were found in the transition from HIGH$_2$ back to LOW$_3$. Figure 3H suggests that ISA ratings decrease during HIGH$_2$, resulting in only a marginal difference between Trial Blocks 8 and 9. To analyze each experimental condition in isolation, separate 4 (block) × 2 (instruction) mixed ANOVAs were conducted for all measures on each of the three experimental conditions. A significant main effect of block was found on ISA ratings during HIGH$_2$, Mauchly's test, $\chi^2(5) = 15.55$, adjusted using Huynh-Feldt, $\varepsilon = .75$, $F(2.25, 47.31) = 3.13$, $p < .05$, $\eta^2_p = .13$. This effect was significant only from Trial Block 5 to Trial Block 7, $F(1, 21) = 5.05$, $p < .05$, $\eta^2_p = .19$, and from Trial Block 5 to Trial Block 8, $F(1, 21) = 14.33$, $p < .01$, $\eta^2_p = .41$.

Furthermore, Figure 3H shows that ISA ratings during LOW$_3$ increase with the driving instruction, whereas they decrease with the equal instruction. A significant interaction between block and instruction was found, Mauchly's test, $\chi^2(5) = 14.43$, adjusted using Huynh-Feldt, $\varepsilon = .80$, $F(2.41, 50.62) = 3.59$, $p < .05$, $\eta^2_p = .15$. Simple contrasts revealed that this interaction was significant from Trial Block 9 to Trial Block 11, $F(1, 21) = 9.93$, $p < .01$, $\eta^2_p = .32$, and from Trial Block 9 to Trial Block 12, $F(1, 21) = 5.07$, $p < .05$, $\eta^2_p = .20$. Memory performance (Figure 3F) appears to follow an inverse trend of the ISA ratings during LOW$_3$: Memory performance decreases with the driving instruction, whereas it slightly increases with the equal instruction. This observation was supported by a significant interaction between block and instruction, $F(3, 63) = 3.00$, $p < .05$, $\eta^2_p = .13$, which was significant from Trial Block 9 to Trial Block 11, $F(1, 21) = 10.12$, $p < .01$, $\eta^2_p = .33$. Last, trends in driving speed appear to decrease during HIGH$_2$ and increase during LOW$_3$, regardless of instruction, but a 4 × 2 ANOVA did not yield any further significant effects.

Impact of Task Prioritization

The manipulation of priority instructions was reflected in mental workload through an interaction effect with period. Surprisingly, this manipulation was not reflected in task performance across the time frame of an experimental condition. The interview results may explain why this was the case. One participant reported that following the driving instruction, she felt “normal, like regular driving.” Another participant with an equal instruction reported, “It was easy to drive, but hard to listen. I concentrated more on the driving task.” These statements suggest that participants had preferences regarding task prioritization that did not always accord directly with the instruction set they received.

To examine whether this conflict played a role, preferences were elicited and then used as an additional between-participant factor. Three raters independently evaluated the interview results to assign a post hoc attribution of a driving or equal preference to each participant. The average agreement between the raters was 71%. Within the driving instruction, 10 participants had a driving preference, whereas one participant had an equal preference. Within the equal instruction, a driving preference was found for eight participants, whereas four participants had an equal preference.

A 2 (preference) × 2 (instruction) × 3 (period) mixed ANOVA was conducted on all measures. The participant with a driving instruction and an equal preference was excluded from this analysis, because there was no variance within this combination. The only significant effect was a main effect of preference on memory performance, $F(1, 19) = 5.17$, $p < .05$, $\eta^2_p = .21$. A driving preference ($M = 53.47\%$, $SE = 2.87$) resulted in lower memory performance than an equal preference ($M = 68.75\%$, $SE = 6.42$). An examination of hysteretic effects through three-way mixed ANOVAs did not yield significant effects involving period (i.e., condition LOW_1 vs. LOW_3) or involving block (i.e., Trial Block 4 vs. 9).

DISCUSSION

The main results of this study are that a hysteretic effect in mental workload was found within the high-demand condition, and contrary to what is commonly reported, no hysteretic effects were observed after the high- to low-demand transition. The latter observation is based on comparisons between relatively long experimental conditions (i.e., a time frame of 8 min) as well as between relatively short trial blocks (i.e., time frames of 2 min). The shortest hysteretic effect that could have been detected with the present setup corresponds with the transition time between the last two experimental conditions (i.e., 106 s) plus the duration of a trial block (i.e., 120 s). From prior work we can postulate that hysteresis likely occurs after a high- to low-demand transition. Thus, if hysteresis took place after the transition from $HIGH_2$ to LOW_3, it must have lasted less than 226 s.

It has been assumed that the present study incorporates two demand transitions large enough to cause hysteresis after the second demand transition (see Figure 5A). However, the present findings challenge this assumption. The auditory memory task may have contributed more to the experienced workload than the driving task, resulting in a limited contrast between LOW_1 and LOW_3 on the one hand and $HIGH_2$ on the other hand (see dark gray blocks in Figure 5B). Support for the contribution of the auditory memory task is found in the fact that the NASA-TLX Mental Demand subscale was rated higher than Physical Demand. The limited contrast follows from the observation that the manipulation of driving task difficulty has resulted in a difference that spans only 12% of the averaged NASA-TLX and a corresponding degree of 11% of the ISA scale. Furthermore, participants may have habituated to the increased driving task demands during $HIGH_2$, especially because driving is an overlearned, everyday task. Although the average ISA rating in $HIGH_2$ was significantly higher than the other experimental conditions, the ratings during $HIGH_2$ were actually decreasing. Consequently, ISA ratings returned to the level of LOW_1 at the beginning of LOW_3. This finding implies that hysteresis had already taken place immediately after the first demand transition (see solid line in Figure 5B).

It is unlikely that resource depletion caused the observed hysteresis in ISA ratings, because task demands were presumably constant throughout $HIGH_2$. The effort regulation theory, which has explained hysteresis in performance in previous work, may also explain hysteresis in mental workload. Our findings support this view. Driving performance and memory performance were unaffected by driving task demand across

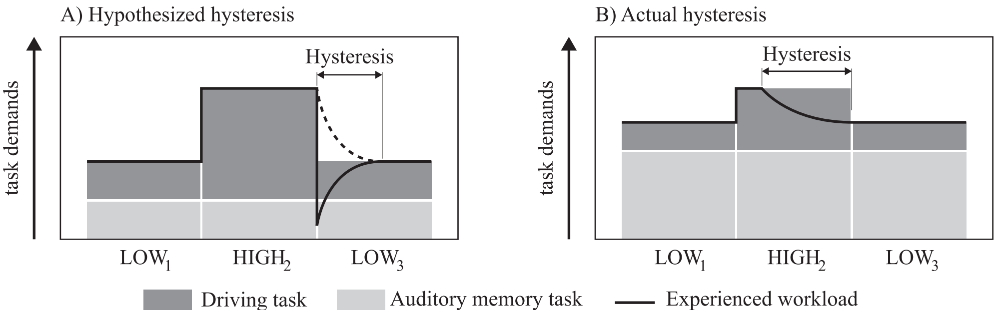

Figure 5. Hypothesized hysteresis (A) and actual hysteresis (B) resulting from demand transitions between experimental conditions. In Panel A the solid line represents hypothesized hysteresis based on Hancock, Williams, and Manning (1995), and the dashed line is based on Morgan and Hancock (2011).

experimental conditions, whereas mental workload increased with driving task demand. The only NASA-TLX subscale unaffected by driving task demand was Own Performance, which apperception was consistent with actual performance. In addition, the Effort NASA-TLX subscale proved to be the main predictor for ISA ratings in HIGH_2. Such findings are consistent with models featuring effort-related adjustment of attentional capacity (Hancock & Warm, 1989; Hockey, 1997). It appears participants improved the efficiency of their coping strategies during HIGH_2, to the extent that similar effort in LOW_1 and LOW_3 was required by the end of HIGH_2.

These findings have several theoretical and methodological implications for future research on demand transitions and resilience (and see Hoffman & Hancock, 2016). First, the observed ISA trends during experimental conditions demonstrate the importance of using online workload ratings in addition to data collected after the cessation of each experimental condition. Second, the intermeasurement time across demand transitions should be minimized, especially if hysteretic effects prove to have a short duration. Physiological measures may help identifying shifts in workload at an earlier instant than ISA ratings. Furthermore, the time it takes to complete a NASA-TLX questionnaire may be inappropriate in such circumstances, even though our results suggest that completion time can itself be greatly reduced through practice. However, the NASA-TLX results have provided valuable information about the nature of experienced workload. The challenge, therefore, is to develop an online rating scale that strikes an appropriate balance between low obtrusiveness (i.e., the unidimensional ISA) and high diagnosticity (i.e., the multidimensional NASA-TLX).

An additional finding of this study is that the manipulation of priority instructions is reflected in mental workload but not in task performance across the time frame of an experimental condition. As a result, the resource depletion and effort regulation theories could not be exhaustively tested as intended through task prioritization. An inquiry into prioritization preferences showed that participants with a preference for the driving task had lower memory performance than those with the equal preference. Therefore, the instructions may have resulted in a significant effect on memory performance, if they matched with preferences. A dual-task study by Jansen et al. (2016) with a low-fidelity driving game suggests that such preferences are guided by judgments on task utility and that conflicting instructions are followed only after extensive dual-task exposure. The present study shows that such a conflict may also play a role in the context of high-fidelity driving simulators. This finding warrants further research into the effect of preferences in combination with other secondary tasks.

ACKNOWLEDGMENTS

We thank Jessica Milos, Emily Simpson, and Gabriel Yeager for their assistance in collecting the data; Tamar Nir for programming support; and Holly Robbins for recording the memory questions.

KEY POINTS

- We investigated carryover workload effects (hysteresis) in participants driving in a simulator. Participants drove a low-workload roadway segment, followed by a high- and a low-workload roadway stretch.
- The unidimensional Instantaneous Self Assessment (ISA) scale obtained subjective mental workload during experimental conditions, and the NASA Task Load Index (NASA-TLX) was used afterward. The relatively nonintrusive ISA proved useful for revealing the evolution of a hysteretic effect in mental workload, whereas the diagnostic power of the NASA-TLX served to interpret this effect.
- The temporal pattern of hysteresis in mental workload informs an appropriate timing of information presentation by communication systems.
- Analysis of verbal reactions suggested that preexisting preferences regarding task prioritization conflicted with priority instructions. Such preferences may be useful to inform personnel recruitment and selection.

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Date received: April 1, 2016
Date accepted: August 3, 2016