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Application of Scheduling Methods in Designing Multimodal In-Vehicle Systems

Changxu Wu[1,2], Omer Tsimhoni[1,2], and Yili Liu[2]
University of Michigan Transportation Research Institute
Department of Industrial and Operations Engineering, University of Michigan

ABSTRACT

Multimodal in-vehicle systems (MIVS) may improve time-sharing performance of drivers. However, it is not always clear for designers of MIVS about how to select appropriate modalities and determine the optimal order of messages presented to a driver. To solve this problem, this paper proposes a general procedure to select several scheduling methods (e.g., Johnson’s rule and non-identical parallel machine scheduling methods) and uses these scheduling methods to assign appropriate modalities and determine optimal order of messages presented to a driver. An empirical study of an example multimodal in-vehicle system was conducted and it validated the effectiveness of scheduling methods as a tool to improve driver performance and reduce driver workload. Further extensions of the current methodology and usage of this general procedure to select other scheduling methods are also discussed.

INTRODUCTION

IMPORTANCE OF MULTIMODAL IN-VEHICLE SYSTEM DESIGN

With the development of technology, there is increased use of various vehicle information systems (e.g., navigation systems, and vehicle status), vehicle safety/warning systems (e.g., collision warning, pedestrian detection systems), and vehicle communication systems (e.g., cellular phones and vehicle-to-vehicle communication). Multitasking between driving and using these systems may impose high information load on drivers, increasing their mental workload (Alm & Nilsson, 1995; Wagner, Vercruyssen, & Hancock, 1997; Wickens, Kramer, Vanasse, & Donchin, 1983), which in turn increases the chance of vehicle collisions compared to a single driving condition (Alm & Nilsson, 1995; Violanti & Marshall, 1996). This introduces a very important topic in in-vehicle system design and transportation safety—how should in-vehicle systems present information without degrading driver performance and increasing driver workload.

Studies in multimodal user interfaces (MUI) suggest that presentation of concurrent tasks via different sensory channels leads to improved time-sharing performance (Sarter, 2001). For in-vehicle systems, multimodal communication between drivers and in-vehicle systems might be an effective way to improve driver performance and reduce information overloading in visual modality (Cellario, 2001; Gupta, Bisantz, & Singh, 2002; Mariani, 2002; Siewiorek, Smailagic, & Hornyak, 2002). Several important qualitative guidelines on how to design multimodal user interfaces have been summarized by Sarter (2001). Computational methods for analyzing multimodal information processing have received only scant attention. Little information exists to assist designers of multimodal in-vehicle systems (MIVS) in selecting appropriate modalities and determining the order of presentation of messages based on the properties of the in-vehicle tasks. In other words, if some basic and/or quantitative information of these tasks are given (e.g., their difficulty levels in the cognitive process, their response modalities (hand or body parts), the distance from the body parts to the in-vehicle devices, etc.), the important question becomes how to assist designers of MIVS so that they can follow a list of algorithms to calculate and select the optimal modality and the order of message presentation to drivers.

At an abstract level of analysis, there are two important dimensions to analyze MIVS as a subset of MUI: 1) At the spatial dimension, MIVS designers need to decide which input modalities of drivers will receive information and which output modalities will execute the control actions; 2) At the temporal dimension, drivers receive a sequence of messages from MIVS and execute a sequence of control movements to manipulate the MIVS interface. If information presented to subjects is regarded as “jobs” and the cognitive system is treated as a group of “processors” or “machines” handling these jobs, then scheduling methods—a group of computational methods that deal with how to arrange the order and assignment of the jobs to machines—can be used to quantitatively analyze human information processing in multimodal human-machine interaction.

REVIEW OF SCHEDULING CONCEPTS AND METHODS WITH THEIR APPLICATION IN MUI

Since the 1950s, scheduling has become a major branch of industrial engineering (French, 1982; Pindo, 2002). Depending on a number of machines in a system and measurements of system performance, many scheduling methods and algorithms have been developed in this area. One of the most commonly used performance measurements in scheduling is makespan (*Cmax*), defined as the duration between when the first job arrives and when the last job leaves the system (French, 1982; Pindo, 2002). *Cmax* might be the performance measurement most relevant to human performance because it is equivalent to the total task completion time in human performance. Table 1 summarizes several scheduling methods depending on configurations and numbers of machines or processors to minimize makespan (*Cmax*) of a system. If machines in a system are arranged in a serial manner (jobs need to go from one processor to another): a) In the single machine condition, since the change of the order of jobs does not affect the makespan, there is no scheduling method developed to minimize *Cmax*; b) When there are two machines or processors arranged in a serial manner, Johnson's Rule is a classic scheduling method to minimize makespan (see description of this rule in detail in the following section of this paper); c) When there are three or more machines, this scheduling problem becomes NP-hard which means there is no polynomial time algorithm to solve it and researchers have to use other methods (e.g., heuristic scheduling methods) to solve these scheduling problems (see (Pindo, 2002) for detailed description of heuristic scheduling methods). In the parallel arrangement situation, depending on the number of processors in a system, the parallel scheduling method (French, 1982) and critical path analysis have been proposed to solve the scheduling problem (see a review of critical path analysis method in (Harold, 2001)) . In the field of multimodal user interface, it seems that only critical path analysis has been used to design multimodal user interface (MUI) (see a review of critical path analysis method in designing MUI in (Baber & Mellor, 2001)) while other simple but effective scheduling methods, including Johnson's Rule, have not been applied, especially to in-vehicle systems.

RELATIONSHIP BETWEEN C_{MAX} (PERFORMANCE) AND SUBJECTIVE DRIVER WORKLOAD

The specific usage of multimodal systems in vehicles and the measurement of subjective driver workload suggest a specific relationship between subjective mental workload and the total in-vehicle task completion time. In driving experiments, the data of subjective workload can only be collected after a driver drives for a certain amount of time with at least several trials of an in-vehicle task; otherwise he or she will not have enough time to experience the workload in using the in-vehicle system.

If we regard the whole cognitive system as a server that processes information from both a road and an in-vehicle system, there is a direct proportional relationship between utilization of this server (ρ) and subjective driver workload (*WL*) (Wu & Liu, In Press):

$$WL=a\rho+b \qquad (1)$$

where a and b are constants depending on different driving situations and in-vehicle systems (a>0). In queueing network theory, utilization (ρ) of a single server can be quantified using the following equation:

$$\rho = \lambda/\mu \qquad (2)$$

TABLE 1 Summary of Scheduling Methods to Minimize Makespan (*Cmax*) of a System

Configuration	Number of Machines	Scheduling Methods	Application in MUI
Serial	Single machine	-	-
	Two machines	**Johnson's Rule**[1]	**Not yet**
	Three or more machine	*NP-Hard* (Heuristic approaches)	-
Parallel	**Two or more machines (machine number < job number)**	**Non-Identical Parallel Machine Scheduling Method**[2]	**Not yet**
	Infinite number of machines (machine number > job number)	Critical Path Analysis	(Baber & Mellor, 2001)

1. Johnson's Rule: Johnson (1954) proposed an optimal scheduling method to arrange the sequence of jobs entering a system in which two machines are arranged in a serial order. The optimal sequence can be obtained by partitioning the jobs into two sets, with Set I containing all the jobs with p1j (processing time of job *j* on machine 1) < p2j and Set II all the jobs with p1j ≥ p2j. The jobs in Set I go first, in increasing order of p1j; the jobs in Set II follow in decreasing order of p2j (Johnson, 1954).

2. Non-Identical Parallel Machine Scheduling Method: Sule (1996) proposed a scheduling method to assign jobs to machines in parallel with different processing times as well as to arrange the order of jobs entering these machines. This method includes three steps (Sule, 1996). Step 1: Rank the m parallel machines such that the most efficient machine (the one taking the least amount of time to process) is machine 1, the next efficient machine is machine 2, and so on. We can also rank the jobs in descending order of processing times, indicating the job with the largest processing time as job 1, the job with the next longest processing time as job 2, and so on. Step 2: Add the processing times of all jobs on machine 1. This is the current value of TT1 (total of processing times assigned to machine 1).

TTi for i=2,3,…m is 0, because no jobs are assigned to machine 2 through m. TT1 is the present value of the makespan. Step 3: Examine the feasibility of reassignment of jobs starting with the first job and proceeding toward job n. To do so, first select the candidate job. Temporarily remove it from machine 1 and assign it to all remaining machines. Reduce the value of TT1 by the processing time of the candidate job. Increase TTi for machine i by the associated processing of the job on that machine and determine the minimum value of TTi for i=2,…m (except ignore TTi =0). The associated processor is where the job should be assigned if it is to be moved from machine 1. Compare the minimum of TTi with TT1 and determine the lower value of the two. If the new value of the makespan is less than the present value of the makespan, make the new assignment permanent and assign the makespan the new value. If the new makespan is not less than the present makespan, the reassignment of this job is rejected. Select the next job in the sequence and repeat the step. If all jobs are examined, stop; we have the best assignment.

where λ is the arrival rate of information and μ is the processing speed of the server. Since *Cmax* is the total task completion time in each trial using the in-vehicle system, it is in inverse proportion to the processing speed of the cognitive system, i.e.:

$$\mu = 1/C_{max} \qquad (3)$$

Combining the equations above, we can easily derive:

$$WL = a\lambda C_{max} + b \quad (a>0) \qquad (4)$$

which indicates a directly proportional relationship between makespan (*Cmax*) and subjective driver workload. In other words, scheduling algorithms that minimize *Cmax* might also be used to reduce the subjective driver workload under the condition that the arrival rate of information remains the same.

A GENERAL PROCEDURE TO SELECT THE SCHEDULING METHODS IN MIVS

Based on the Theory of Constraints (TOC) and general procedure of applying scheduling methods in practice (McMullen, 1998; Pindo, 2002), a general procedure was proposed to select and use scheduling methods in designing MIVS. In addition, in order to illustrate the procedure clearly, the following definitions were used:

STEP 1. IDENTIFY STATUS OF A INFORMATION PROCESSING STAGE

The following rules can be used to determine the serial or parallel processing at each processing stage (perceptual, cognitive, and motor stages). Each job/task to be analyzed first needs to be decomposed into one, two, or three of the three major stages of information processing. Second, it is necessary to identify the information processing status of each stage is serial or parallel. For example, if one of the three stages can process information at the same time (e.g., the right hand is operating an in-vehicle device while the right foot is pressing a break), this stage can be regarded as a parallel stage (PS). On the other hand, if a stage can only handle the information/jobs one by one, this stage is regarded as a bottleneck stage (BS) (e.g., in the cognitive stage, subjects can only perform one arithmetic problem at one time; Pashler, 1984).

STEP 2. CHOOSE THE CORRESPONDING SCHEDULING METHODS AND SCHEDULE THE JOB AT EACH STAGE

Once the status of a stage is identified (BS or PS), the second step is to select the scheduling methods to arrange the order of jobs based on following rules:

1) 1 BS (there is only one BS in the cognitive system based on the current task setting)
If PS (Number of PS>=1) is identified in the system:
→ Use Non-Identical Parallel Machine Scheduling Method to schedule each PS
Else: No scheduling method is recommended for this situation since change of job orders will not affect *Cmax* and workload
2) 2BS (there are two BS in the cognitive system based on the current task setting)
2BS+1 PS: Use Non-Identical Parallel Machine Scheduling Method to schedule the PS
If the 2 BS are connected directly → Use Johnson's Rule
Else→ Only schedule the PS using Non-Identical Parallel Machine Scheduling Method
Only 2BS: → Use Johnson's Rule
3) 3BS: Use heuristic scheduling methods
4) 0 BS: No scheduling method is recommended for this situation since change of job orders will not affect *Cmax* and workload

STEP 3. REARRANGE THE ORDER OF JOBS OR/AND REASSIGN THE JOBS TO AVOID INCONSISTENCY

Step 2 may generate different job orders or different assignment of jobs in different stages. If this happens, considering the nature of human information processing, changing the order of jobs within the cognitive system may increase incompatibility between the stimuli order and the order of mental and/or motor processing, causing extra load on the cognitive system (Kok, 2001). Therefore, it is recommended to keep the order and assignment of jobs the same with the scheduling results (job orders and assignment of jobs) of the stage with longest processing time which can be estimated via GOMS (Goal, Operators, Methods, Selection) (Olsen & Olsen, 1990), MHP (Model Human Processors) (Card, Moran, & Newell, 1983), or QN-MHP (Wu & Liu, In Press).

STEP 4. VALIDATE THE SCHEDULING RESULTS WITH SIMULATION OR EXPERIMENT AND DESIGN THE MIVS BASED ON THE VALIDATED SCHEDULING RESULTS

The following section describes a case study in using the scheduling methods and procedure to select optimal modality and job orders when drivers are operating a multimodal in-vehicle system.

A CASE STUDY

AN EXAMPLE MULTIMODAL IN-VEHICLE SYSTEM WITH PRACTICAL IMPORTANCE

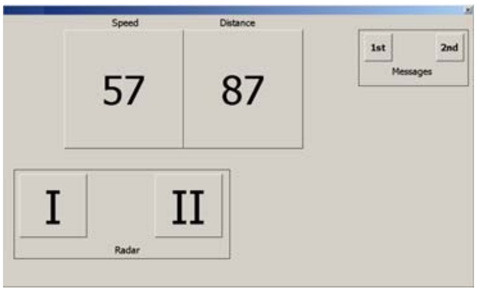
According to a report from NHTSA's National Center for Statistics and Analysis, speeding is one of the most prevalent factors contributing to traffic crashes: The economic cost to society of speeding-related crashes is estimated by NHTSA to be $40.4 billion per year; in 2004, speeding was a contributing factor in 30 percent of all fatal crashes, and 13,192 lives were lost in speeding-related crashes (Ewing, 1999 ; NHTSA, 2004). Traffic law enforcement (police officers detecting speeding and issuing speeding tickets) is one of the most critical measures to prevent speeding. However, besides detecting speeding, police officers also have to perform other tasks at the same time, e.g., communicating with dispatchers, navigating the vehicle to a target location, etc.

Based on an informal interview with four police officers at the public safety service center at the University of Michigan, it was found that one of their representative multitasking scenarios is to perform the following two tasks while they are steering vehicles. Speeding detection or judgment task (Subtask 1): Officers need to read two numbers on a display of an in-vehicle radar system mounted on dashboards of police vehicles. The first number is the speed of a target vehicle measured by the radar system; the second is the distance from the police vehicle to the target vehicle. Whether the target vehicle is speeding is determined by both the speed and the distance. Radio message response task (Subtask 2): Messages received by the officers usually came from multiple sources (headquarters, other police officers, and maintenance), and the officers need to respond to higher priority messages (e.g., headquarters) by pressing a button on the radio.

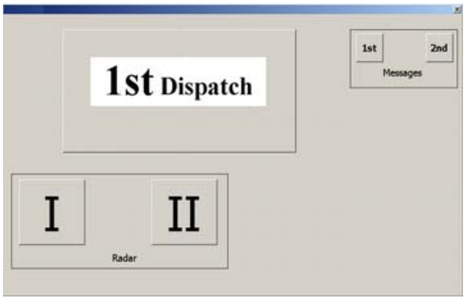
This sample multiple task can also be generalized into other multitasking situations in driving since it captures two important characteristics of multitasking in driving: 1) Multitasking information in driving is typically presented in a multimodal format: either at the visual (e.g., looking at a map or a display of a navigation system) or the auditory modality (e.g., listening to messages from celluar phones or warning systems) and 2) It covers perceptual, cognitive, and motor processing. For example, the speed detection task might be close to a secondary task in using a navigation system while driving: Drivers read directions for the next turn and distance to the next turn from the display (perceptual processing), perform mental calculations to decide whether and when to switch to a different lane (cognitive processing), use the turning signal and turn the steering wheel (motor processing).

EXPERIMENTAL SETTING OF THE EXAMPLE MULTIMODAL IN-VEHICLE SYSTEM

The use of scheduling methods is able to assist designers of these multimodal in-vehicle systems in selecting the optimal modality and determine which task is to be presented to drivers earlier. In this specific scenario, there are four possible combinations of modality and order of tasks. For example, the message-response task was presented in the auditory modality (AUD) prior to the radar judgment task shown in visual modality (VIS) (Mesg_AUD condition); similarly, the other three conditions are Mesg_VIS, Radar_AUD, and Radar_VIS. Figure 1 shows the user interface of the multimodal system which includes the two pairs of response keys for the radar judgment and message response task (the response keys of message-response task were located 13 cm away from the response keys of the radar judgment task).



Mesg_AUD and Radar_VIS Conditions



Mesg_VIS and Radar_AUD Conditions

FIGURE 1. The user interface of the multimodal in-vehicle system

For the message response task, whenever subjects heard or saw the word “first dispatches” (the presentation duration of the word “first” was 300 ms in the auditory modality, and 5 seconds in the visual modality) from the speakers or the touch screen, they were asked to double click on the “1st” button on the touch screen with their right index fingers; if they heard or saw “second dispatches” (the presentation duration of the word “second” was the same with that of word “first”) , they were instructed to double click on the “2nd” button on the touch screen with the same fingers.

For the radar judgment task, subjects were asked to judge the level of speeding of another vehicle based on speed and distance information from the speakers or the touch screen the using following rules (the presentation duration of the speed and distance information were 850 ms in the auditory modality, and 5 seconds in the visual modality): a) If the speed is within the range of 55 to 60 (including 55 and 60), they need to see the distance: If the distance is beyond 65 yards (including 65), they were asked to press the “II” button because it is moderate speeding (level II). If the distance is below 65 yards, they were instructed to press the “I” button since it is severe speeding (level I). b) If the speed is above 61 (including 61), they need to see the distance: If the distance is beyond 105 yards (including 105), it is moderate speeding (level II) and subjects were asked to press “II” button; if the distance is below 105 yards, subjects were instructed to press “I” button because it is severe speeding (level I).

ARRANGEMENT OF MODALITY AND JOB ORDERS BASED ON THE GENERAL PROCEDURE

Step 1. Identify Status of a Information Processing Stage

Since both the message-response task and radar judgment task involved decision making or judgment process in the cognitive stage, the cognitive stage was regarded as a bottleneck stage (BS) (Pashler, 1984). Because the information of the two tasks was processed through different sensory modalities, the perceptual stage was regarded as a parallel stage (PS). In addition, pressing the touch screen using the same finger implied a strictly serial processing at the motor processing stage for the two tasks (BS). Accordingly, a simplified configuration of the cognitive system in this specific scenario is summarized in Figure 2.

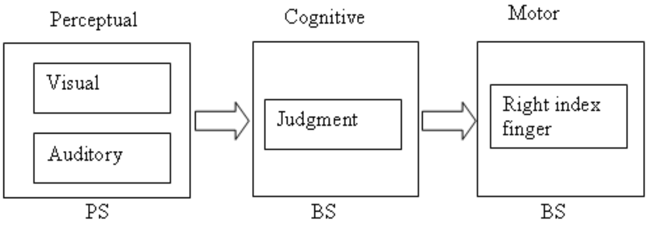


FIGURE 2. Status of stages in the cognitive system in performing the tasks in the case study.

Step 2: Choose the Corresponding Scheduling Methods and Schedule the Job at Each Stage

Based on the general procedure and analysis of the status of stages in the current task setting, it is recommended to use Johnson’s rule to schedule the jobs in the two bottleneck stages and use non-identical parallel machine method to schedule the jobs in the PS.

Scheduling 2-Bottleneck (Cognitive and Motor Stage) Using Johnson’s Rule. Based on the current design of the experimental task, $\text{Judgment}_{\text{mesg}} < \text{Judgment}_{\text{radar}}$ (complex rule operations of the radar task in the judgment process compared with the simple choice reaction in the message response task) and $M_{mesg} > M_{radar}$ (longer movement distance and double click movement in the message task compared to the smaller movement distance and single click in the radar task). According to Johnson’s Rule, the message-response task (called “Message Job/Task”, *Jm*) was assigned to Set I and the radar judgment task based on the radar’s detection results (called “Radar Job/Task”, *Jr*) was assigned to Set II. The order that these jobs enter the judgment process is *Jm* and then *Jr*. Accordingly, *Jm* should be presented to subjects earlier than *Jr* (order of tasks). In order to guarantee that *Jm* arrives at the judgment process earlier than *Jr*, *Jm* should preferably be presented at a faster modality (modality of tasks). In the current experiment setting, auditory modality is the faster modality compared with visual modality because in the driving condition, it took drivers at least one glance to shift their fixation from a curved road to the visual stimuli of the in-vehicle task (Tsimhoni, Yoo, & Green, 1999)compared with the condition when this information was presented in the auditory modality without eye movements. Therefore, *Jm* is assigned to the auditory modality so that the chance that *Jr* catches *Jm* and arrives at the judgment process is lower in the Mesg_AUD condition compared with the Mesg_VIS condition.

Scheduling Perceptual Stage with Non-Identical Parallel Machine Method. Because the perceptual stage is composed of multiple sensory modalities arranged in a parallel manner, the parallel non-identical machine scheduling method can be applied to arrange jobs/tasks in different modalities. Table 2 summarizes the estimation of processing time at the auditory and visual modalities based on the current scenario.

TABLE 2 Estimated Processing Time of the Two Tasks in the Auditory and Visual Modalities

	Estimated Processing Time of the Two Tasks		
Modality /Processor	Message (*Jm*)	Radar (*Jr*)	Average
Auditory (P1)	300 ms (experiment setting)	800 ms (experiment setting)	550 ms
Visual (P2)	676 ms[1]	676 ms	676 ms
Average	488 ms	738 ms	

1. This processing time was estimated based on the number of glances multiplied by glance duration looking at an in-vehicle system: 1.9 glances for an in-vehicle task with similar level of task difficulty (Tsimhoni et al., 1999); The duration of each glance was estimated based on MHP (Card et al., 1983) and QN-MHP (Liu, Feyen, & Tsimhoni, 2006): 230 ms (average eye movement time) +126 ms (42*3=126: servers' processing time at the visual stage/subnetwork. Therefore, 1.9*(230+126)=676 ms.

Step 1). Rank the processing time of processors and jobs
Efficiency of processors: auditory modality (P1) faster than visual modality (P2)
Processing time of jobs: *Jr*>*Jm*

Step 2). Put all of the jobs at P1 with descending order of processing time
Jr (Job 1), *Jm* (job 2)→P1 (Auditory)

Step 3). Move longest job (job1) from P1 to other processors
Jm→ P1 (Auditory), *Jr*→ P2 (Visual)
=>*Cmax*=max(300, 676)=676 ms

Step 4). Move job 2 from P1 to other processors
Jr→ P1 (Auditory), *Jm*→ P2 (Visual)
=>*Cmax*=max(800, 676)=800 >676 → Reject

Therefore, *Cmax* can be reduced if we assign *Jm* to auditory modality and *Jr* to visual modality.

Step 3. Rearrange the order of jobs or/and reassign the jobs to avoid inconsistency

Since the application of scheduling methods in the three stages in the step 2 produced the same scheduling results (message response task was presented in the auditory modality and it occurred earlier than the radar judgment task shown in the visual modality), it was not necessary to rearrange the order of jobs to avoid inconsistency.

Step 4. Validate the scheduling results with simulation or experiment and design the MIVS based on the validated scheduling results (see the following section for validation of the scheduling results).

EXPERIMENTAL VALIDATION

As described in the first section of the case study, it is predicted that the MESG_AUD condition selected by the scheduling methods should produce the minimal total task completion time and lowest subjective workload. An experiment was conducted to validate this prediction, as described in the following section.

Experimental Design

A one-factor within-subject design was used in this experiment. The independent variables were the four combinations of modality and order of tasks as described in the first section of the case study: Mesg_AUG, Mesg_VIS, Radar_AUD, and Radar_VIS. The dependent variables were the makespan (total task completion time) of the secondary task (the in-vehicle task composed of message response and radar judgment tasks), error rate of the secondary task, subjective workload measured by NASA-TLX, and driving performance measured by standard deviation of lane position. Each participant used the in-vehicle system in all of the four combinations of modality and order of tasks. The order of the four combinations for each participant was arranged following a Latin Square design so that the four combinations appeared first, second, third, or fourth for exactly one participant.

Participants

Sixteen licensed drivers were paid to participate in this experiment (ages 25-34 years, mean=31, SD=2.5; 8 male and 8 female). All participants were right-handed and had corrected far visual acuity of 20/40 or better. All had midrange (80 cm) visual acuity of 20/70 or better. Prescreening of all participants ensured they had good driving records and were physically healthy.

Equipment and Test Materials

Driving Simulator. The simulator consisted of a full-size cab, computers, video projectors, cameras, audio equipment, and other items. The simulator has a forward field of view of 120 degrees (3 channels) and a rear field of view of 40 degrees (1 channel) (See Figure 3). The forward screen was approximately 16-17 feet (4.9-5.2 m) from the driver's eyes, close to the 20-foot (6 m) distance often approximating optical infinity in accommodation studies. The vehicle mockup consisted of the A-to-B pillar section of a 1985 Chrysler Laser with a custom-made hood and back end. The main simulator hardware and software was a DriveSafety Vection simulator running version 1.6.1 of the software.

FIGURE 3. UMTRI DRIVING SIMULATOR

Simulated Road. The simulated road had a 250 m radius curvature. Both lanes of the two-lane road were 3.66 meters (12 feet) wide. The length of the road in each condition of the in-vehicle system was 5,000 meters with 4 speed-limit signs (65 mph, 104 km/h) placed in the road at every 1,250 meters.

Touch Screen. An IBM laptop X60 with a 12'' touch screen was mounted to the right of the driver at arm's length. This touch screen was located in the center console of the vehicle, 23° ± 3° below the horizontal line of sight and 30° ± 3° to the right of the center. To allow easy reading, numbers on the display were relatively large (digit height = 11 mm, 1° at 63 cm).

Experimental Task and Procedure

Driving Task. Participants were instructed to drive in the right lane and maintain a speed following the speed-limit signs on the simulated roads. To maintain driving speed, participants driving 5 mph (8 km/h) over or below the speed shown on the speed-limit signs heard a computer-generated voice "too fast" or "too slow."

Secondary Task. The secondary task was composed of two tasks (message response and radar judgment) as described in the first section of this case study. Participants were asked to complete the tasks as quickly and accurately as possible.

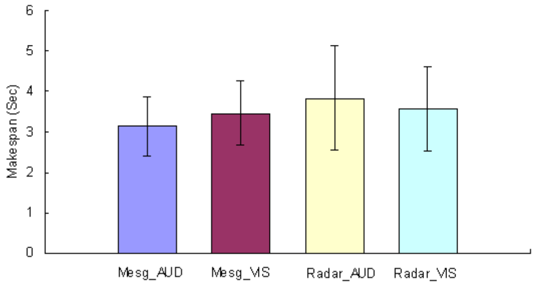
Experimental Procedure. After filling in the pretest forms and receiving a vision test, participants had a practice session, first with the single task of driving without a secondary task, and then with the secondary task while the simulator was in parked condition. Then, participants practiced the dual task situation: driving while performing the secondary task at the same time. In the test section, participants were instructed to drive with the multimodal system in its four conditions (participants drove 5,000 meters in each condition). After participants finished each condition, they were asked to complete the NASA-TLX form to report their subjective workload.

Experimental Results

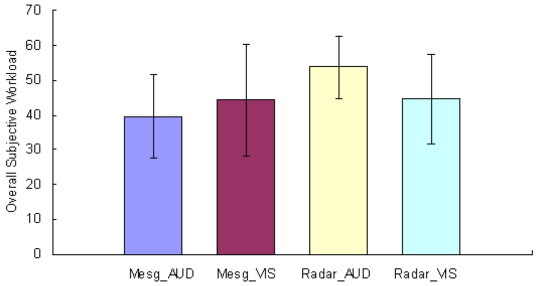
Performance of the Secondary Task. Figure 4a shows the average makespan in the four combinations of modalities and order in driving conditions. The main effect of the four combinations of modality and order on makespan was significant (F(3,45)=14.46, $p<.001$). The tests of one-factor within-subject contrasts (treating the four combinations of modalities and order as one within-subject variable) found a significant difference between the Mesg_AUD with other conditions (Mesg_AUD vs. Mesg_VIS: F(1,15)=16.61, $p<.001$; Mesg_AUD vs. Radar_AUD: F(1,15)=62.85, $p<.001$; Mesg_AUD vs. Radar_VIS: F(1,15)=49.96, $p<.05$).

In addition, the main effect of the four combinations of the modality and order on error rate of the secondary task was not significant (F(3, 45)=1.64, $p>.05$). Furthermore, the error rates of the Mesg_AUD condition were not significantly different from the other three combinations of the modality and order (Mesg_AUD vs. Mesg_VIS: F(1,15)=1.59, $p>.05$; Mesg_AUD vs. Radar_AUD: F(1,15)=1.56, $p>.05$; Mesg_AUD vs. Radar_VIS: F(1,15)=.65, $p>.05$).

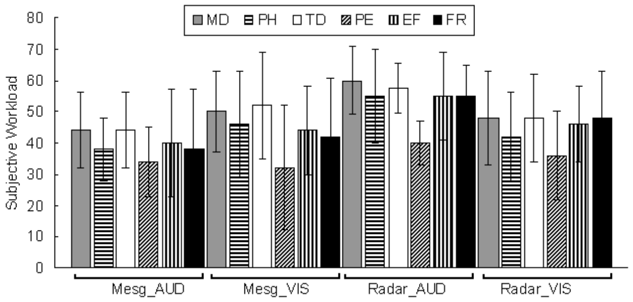
Mental Workload. Figure 4b shows the overall subjective workload measured by NASA-TLX in the four combinations of modality and order. The main effect of the four combinations of modality and order on mental workload was significant (F(3, 45)=19.98, $p<.001$). The overall workload of the Mesg_AUD condition was significantly lower than the other conditions (Mesg_AUD vs. Mesg Vis: F(1,15)=6.05, $p<.05$; Mesg_AUD vs. Radar_AUD F(1,15)=43.75, $p<.001$; Mesg_AUD vs. Radar_VIS: F(1,15)=6.51, $p<.05$). Figure 4c presents the comparison of subjective workload between Mesg_AUD and the other three conditions in the six dimensions measured by NASA-TLX. In the mental demand (MD), physical demand (PD), and temporal demand (TD) dimensions, the subjective workload of Mesg_AUD at Mesg_AUD was significantly lower than Mesg_VIS and Radar_AUD conditions; in the effort (EF) and frustration (FR) dimensions, the subjective workload of Mesg_VIS was significantly lower than all of the other conditions; however, in the performance (PE) dimension, subjective workload of Mesg_AUD was only significantly lower than of Mesg_AUD (See Table 3). In addition, the main effect of combinations on the subjective workload of the six dimensions of NASA-TLX was significant except for the PE dimension (MD: F(3, 45)=18.01, $p<.001$; PH: F(3, 45)=27.30, $p<.001$; TD: F(3, 45)=10.06, $p<.001$; PE: F(3, 45)=1.92, $p>.05$; EF: F(3, 45)=20.60, $p<.001$; FR: F(3, 45)=21.97, $p<.001$).



a) The average makespan in the four combinations of modalities and orders. (Error bars represent ±1 SD of *Cmax*)



b) Overall subjective workload in the four combinations of modalities and orders. (Error bars represent ±1 SD of the overall subjective workload)



Mental Demand (MD), Physical Demand (PH), Temporal Demand (TD),Performance(PE), Effort (EF), Frustration (FR)

c) The six dimensions of subjective NASA-TLX workload in four combinations of modality and order.
(Error bars represent ±1 SD of the subjective workload)

Figure 4. Experimental results of driver performance and mental workload

TABLE 3 Comparison of Mesg_AUD Condition with the Other Conditions in the Six Dimensions of NASA-TLX

Dimensions	Comparison	F(1,15)	Sig	Dimensions	Comparison	F(1,15)	Sig
Mental Demand (MD)	Mesg_AUD vs. Mesg_VIS	5.95	*	Performance (PE)	Mesg_AUD vs. Mesg_VIS	.32	
	Mesg_AUD vs. Radar_AUD	22.84	**		Mesg_AUD vs. Radar_AUD	5.95	*
	Mesg_AUD vs. Radar_VIS	2.14			Mesg_AUD vs. Radar_VIS	.17	
Physical Demand (PH)	Mesg_AUD vs. Mesg_VIS	15.00	**	Effort (EF)	Mesg_AUD vs. Mesg_VIS	11.67	**
	Mesg_AUD vs. Radar_AUD	55.51	**		Mesg_AUD vs. Radar_AUD	33.99	*
	Mesg_AUD vs. Radar_VIS	2.049			Mesg_AUD vs. Radar_VIS	7.64	**
Temporal Demand (TD)	Mesg_AUD vs. Mesg_VIS	5.99	*	Frustration (FR)	Mesg_AUD vs. Mesg_VIS	11.67	**
	Mesg_AUD vs. Radar_AUD	23.50	**		Mesg_AUD vs. Radar_AUD	34.61	**
	Mesg_AUD vs. Radar_VIS	2.14			Mesg_AUD vs. Radar_VIS	40.00	**

*: *p*<.05; **: *p*<.01

Driving Performance. The main effect of the four combinations of the modality and order on the standard deviation of lateral lane position was not significant (F(3,45)=1.05, *p*>.05). Furthermore, standard deviation of lateral lane position of Mesg_AUD was not significantly different from the other three combinations of the modality and order (Mesg_AUD vs. Mesg_VIS: F(1,15)=1.07, *p*>.05; Mesg_AUD vs. Radar_AUD: F(1,15)=.18, *p*>.05; Mesg_AUD vs. Radar_VIS: F(1,15)=2.04, *p*>.05).

DISCUSSION

This study proposed a general procedure to apply several scheduling methods to the design of multimodal in-vehicle systems, including how to select the modalities and arrange the order of tasks. It applied two scheduling methods—Johnson's Rule and non-identical parallel machine scheduling—to human factor research in transportation. The general procedure and scheduling methods described in this study can also be applied to the design of multimodal user interface in other human-machine systems.

The case study in the current work used a small number of tasks and considered the two most commonly used modalities (visual and auditory) in human-machine interaction. However, when the number of tasks or modalities increases because of increased usage of in-vehicle information/warning/security systems, it becomes more effective to use these scheduling methods to design multimodal in-vehicle systems. For example, if there are four messages to be processed by a driver in visual, auditory, and tactile modalities (e.g., Message 1 from road guidance system, Message 2 from vehicle status monitoring system, Message 3 from vehicle-to-vehicle communication system, and Message 4 from cellular phone), the minimal number of full combinations of modality and order is: 3×2×1×3×2=36 (3 (The first message can be assigned to one of the three modalities) ×2 (the second message can be assigned to the two modalities left) ×1 (the third message is assigned the last modality) ×3 (the fourth message restarts this process) ×2 (the order of 4th message and one of the previous messages also need to be considered)=36). In practice, it might be very time-consuming to test all of the possibilities of modalities and orders, while using the scheduling methods described in this paper can save part of the effort and allow selecting the optimal combinations by following some algorithms.

More importantly, the current general procedure can be a platform for human factors researchers to select other scheduling methods that can consider other aspects of jobs (e.g., priority, number of tardy jobs, etc.). For example, if it is decided that there are two serial stages connected directly, even though it is difficult to use Johnson's Rule to arrange the jobs with priority, we can use the general procedure to select scheduling methods which can handle this problem since the taxonomy of scheduling methods are organized in this manner (starting from a single machine, multiple machines, and parallel machine, etc.). Users can easily access these scheduling methods via the major reviews and text books in scheduling theory (French, 1982; Pindo, 2002; Sule, 1996) and even use free scheduling software (e.g., LEKIN® developed by School of Business at New York University). Many scheduling algorithms are very complex, using dynamic programming and artificial intelligence techniques that are far beyond the scope of human factors and transportation safety research. Therefore, the critical task becomes how to define a human-machine problem into a scheduling problem and select a proper scheduling method to solve this problem since the algorithms themselves have been coded in these scheduling software. Accordingly, before researchers in human factors and transportation safety use these scheduling methods, the general procedure proposed in this paper can assist them to select and use these complex scheduling methods.

There are several limitations of the current work that need to be examined in future research. First, the current scheduling methods and general procedure introduced cannot predict the makespan (total task completion time) and workload of drivers. They can suggest modalities and order only at an ordinal scale. In many cases, these ordinal results can satisfy the purposes of designing in-vehicle systems. However, new algorithms or simulation models are needed if a designer hopes to compare the makespan and workload at the interval or ratio scale. Second, Step 1 in the current general procedure uses a relatively simple and qualitative method to determine the status of stages whether it is serial or parallel. However, in many real situations, it may not easy to differentiate the status of a stage with this qualitative method; and we are developing computational/quantitative methods (including QN-MHP) (Wu & Liu, In Press) so that designers are able to use them to determine the status of stages in this step. Third, the modality shifting effect (Spence & Driver, 1997) was not considered in the current work because the order of tasks within each condition of the in-vehicle system was fixed, while the modality shifting effect is mainly related to a shift of modalities in an unexpected condition. Future research that can predict the makespan and workload needs to consider this important effect in multimodal research, either as part of the delay time of the second task/job entering the cognitive system or by prolonging the perception time of the second task.

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CONTACT

Changxu (Sean) Wu is an Assistant Professor in the Department of Industrial and Systems Engineering at State University of New York (SUNY)-Buffalo.

Postal Address: 414 Bell Hall, University at Buffalo, Buffalo, NY, 14260-2050

Email:changxu@buffalo.edu

Phone: (716) 645-2357 Ext 2184

Homepage:
http://www.acsu.buffalo.edu/~changxu/

Lab Website:
http://www.acsu.buffalo.edu/~changxu/index_Lab.html