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Unintended Acceleration: A Review of Human Factors Contributions

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The evidence is reviewed for a human factors explanation of the phenomenon of *unintended acceleration*, whereby at the start of a driving cycle an operator experiences full, unexpected acceleration for as long as 12 s with an apparently complete failure of the braking system, often leading to an accident. There is strong support for the view that the right foot contacts the accelerator even though the driver fully intended to press the brake because of inconsistency in foot trajectory generated by spinal- or muscle-level variability. There is considerable evidence that the variable, inconsistent processes that generate muscular forces and their timing are the source of these errors. Issues related to the reasons the driver is not aware of such errors and why they can persist for so long are reviewed. In view of this evidence, future examinations of this problem should be directed toward a fuller understanding of motor control processes in pedal operation.

INTRODUCTION

A few drivers of nearly every make of automobile with automatic transmissions have experienced the situation in which, after shifting the transmission selector from Park to either Drive or Reverse the automobile accelerates suddenly and violently without warning, with the driver claiming that the right foot was pressed firmly on the brake pedal during the episode. These relatively rare occurrences of *unintended acceleration* as the phenomenon has been termed, are at best extremely frightening and at worst have resulted in various accidents in which the vehicle has collided with objects nearby, sometimes with injuries or death to the driver or pedestrians. The typical case begins at the start of a driving cycle after the driver has entered the vehicle. Drivers frequently report that they started the engine and pressed the brake pedal in normal preparation for driving and that as the gear selector was moved to D or R, full, unexpected acceleration either forward or backward occurred simultaneously with a complete failure of the braking system. The drivers emphatically maintain that their right foot was on the brake, that the pedal could be depressed easily to the floor, and that the pedal was completely ineffective in halting the acceleration. The episodes might last from less than 1 s to as long as 12 s, with the vehicle attaining speeds in excess of 64 km/h before a violent collision occurs. Immediately after the accident, tests of the brake and fuel delivery systems reveal that they are functioning normally.

The causes of such accidents have been

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sought in a variety of engineering analyses dating to the late 1940s (G. R. Gallaway, personal communication to Volkswagen of America, Troy, MI, 1987), usually focusing on potential electromechanical bases for the problem such as failures in cruise control mechanisms, fuel delivery systems, or onboard processors that control fuel mixtures and electrical events (see Pollard and Sussman, 1989, for a review). However, despite the efforts of several automobile manufacturers to identify the difficulty, no mechanical basis for the problem has been found which would account for the simultaneous catastrophic failure of acceleration and braking systems, with a sudden return to normal after the accident. In addition, these accidents have occurred in nearly every make of vehicle with automatic transmissions (almost never with manual transmissions) in which the general design of the fuel delivery systems, brakes, transmissions, and linkages has been vastly different between vehicles, making a common design problem unlikely.

Several lines of evidence lead to the suspicion that the problem is not mechanical. Sufficient numbers of such accidents have occurred that a list of several driver risk factors was recently compiled (National Highway Traffic Safety Administration, 1987) suggesting that the issue is related to human factors. The accidents occur much more frequently as driver age increases: there is a 100%–600% overinvolvement of drivers older than 60 years (normalized for miles driven per year) and underinvolvements of drivers 15–40 years of age. In addition, the accidents occur most frequently in relatively new vehicles and in vehicles with which the drivers are relatively unfamiliar (Perel, 1983; Tomerlin, 1988). There are also slight tendencies for these accidents to occur more frequently among women than among men and among people shorter than average. If the problem were purely mechanical, it is difficult to imagine how such driver characteristics as age and vehicle familiarity could be related to the incidence of these accidents. A more profitable approach to the problem, therefore, is to consider the possibility of some kind of human failure and/or a particular driver-vehicle interaction that can lead to these episodes.

One explanation involves the driver making a foot-placement error while shifting from Park to either Drive or Reverse, essentially resulting in the accelerator being contacted rather than the brake, a slip from the brake to the accelerator, or perhaps both pedals being contacted at the same time. If the accelerator were pressed firmly, as it would be if the driver believed it to be the brake pedal, the result would be strong acceleration of the automobile shortly after the transmission selector was moved combined with the driver's perception that the brakes had suddenly failed, as the accelerator pedal would be easily depressed to the floor.

However, as logical and simple as this viewpoint may sound, a number of other aspects of this phenomenon at first glance make such simple human factors accounts difficult to believe. First, what is the source of such foot placement errors? Why would experienced drivers, often with hundreds of thousands of miles of experience throughout their lifetimes, suddenly make such errors, and what are the physiological and psychological processes that precipitate them? Second, even if the wrong pedal were contacted, why would the driver not perceive this error immediately? The brake and accelerator pedals are in different places with respect to the driver's body, and the dynamic "feel" of these two pedals is considerably different, making it difficult to understand how such an error would not be detected easily. Third —and perhaps most puzzling— why would the driver persist in pressing the wrong pedal for sufficient time that an accident could occur, in some cases for as long as 12 s? Usually ample time for corrective action (to turn off the ignition or shift to Neutral or Park) is available, and yet the drivers typically report no attempts to take such action until the accident occurs, bolstering their belief in a mechanical cause.

These and other questions seem to contradict our common understanding of driving behavior, as it is difficult (especially for those involved in the accidents) to imagine how such an account of driver behavior could be correct. However, the research literature on movement control and human factors does provide a reasonably strong basis for explaining these apparent contradictions. This article summarizes the research literature pertinent to several closely related human performance accounts of unintended acceleration in terms of foot-positioning errors. The sections are organized around the foregoing questions concerning how such errors occur, why they are not detected, and why they persist for so long before an accident occurs.

Before turning to the theories of unintended acceleration and the evidence for them, support for the general view that foot placement errors are involved in these accidents is presented. Several lines of evidence from accident reports as well as laboratory simulations of driving situations support this general view relatively well.

EVIDENCE OF DRIVER ERRORS IN FOOT PLACEMENT

Accident Reports

Several studies of accident reports are available, but the most useful for the present purposes comes from Perel (1976) involving nearly two years of data from North Carolina: 95 879 accidents in 1974 and 19 017 accidents in 1975. Police reports taken at the scene shortly after the accident were analyzed for key words related to foot movement errors. Of these reports, 62 contained key words related to the various problems of foot placement which appeared to lead to the accident. Of these 62 cases, 12 were caused by contacting the accelerator rather than the brake and another 21 were caused by the foot slipping from the brake onto the accelerator. I have also reviewed accident reports taken from North Carolina during 1982–1983 which were selected because of admitted pedal errors; in 91 accident reports relevant to this issue, 80 had statements indicating the accelerator was pressed rather than the brake, with several others leaving this as a strong possibility. It is clear that the error involving moving to the accelerator rather than the brake is a well-documented, though perhaps rare (0.03% of the cases in Perel, 1976), event in normal driving (see also Tomerlin, 1988; Tomerlin and Vernoy, 1988).

However, this low incidence of reported accelerator-brake errors probably greatly underrepresents the number of such errors in everyday driving. An unknown number of similar errors could have been made which did not result in a reportable accident and were therefore undetected in this study. In addition, these are reports of admitted errors, and it is reasonable to assume that not all of the drivers who experienced such errors admitted them to the authorities at the accident scene. Third, Perel found a group of 36 so-called "brake failure" errors—different from the foot movement errors categorized here—some of which could have involved the accelerator being pressed instead of the brake. The subjective impression in such instances would have been of brake failure—the driver might not have been aware of the error even after the accident occurred. Several of these occur in the 1982–1983 data set as well.

Driver Inexperience with the Accident Vehicle

Studying automobile and motorcycle accidents, Perel (1983) reported strong documentation that drivers with relatively little experience with the accident vehicle (essentially independent of driver experience generally) were significantly overrepresented in the accident data. For example, drivers who had driven the accident vehicle 500 miles or less (including borrowed or rented vehicles) represented 12% of all accident-involved drivers; those drivers with less than 2000 miles of experience of the vehicle accounted for 25% of the accidents (see also Tomerlin, 1988). Perel suggested that at least some of this problem is related to unfamiliarity with the foot controls (Glaser and Halcomb, 1980, Glass and Suggs, 1977). There is strong evidence that drivers new to their vehicles tend to have more unintended acceleration episodes. This applies not only to new owners but also to occasional users such as parking lot attendants or rental car patrons who are relatively unfamiliar with the controls in a particular vehicle.

Experimental Studies of Foot Movement Errors

In laboratory simulations of driver behavior, several studies document the frequency of foot placement errors. In studying movement times from the accelerator to the brake, for example, Glass and Suggs (1977) found that subjects occasionally caught their feet on the brake pedal, representing an error in aiming the foot at the brake and suggesting that foot placement is not always perfectly executed. However, in a systematic study of foot placement errors, Rogers and Wierwille (1988) examined subjects in a simulated driving task with four different pedal configurations. Various foot movement errors (297 errors of various types) were relatively frequent, with four errors occurring for every hour of driving, or one error out of approximately 24 foot movements, on the average. However, pressing the accelerator instead of the brake was relatively rare, occurring in only two instances in the entire experiment. When this error was made, the driver always corrected it immediately, unlike the situation in the typical unintended acceleration incident. A related error wherein both pedals were depressed simultaneously when only the brake was intended was considerably more frequent (10 errors recorded) and might also be involved in the unintended acceleration situations of interest here. Finally, Tomerlin and Vernoy (1988) videotaped 14 instances of subjects pressing the accelerator rather than the brake and 12 additional movements in which both pedals were contacted out of 258 foot movement attempts (129 different subjects) in actual (static) vehicles. Those drivers were generally unfamiliar with the test vehicles, which perhaps somewhat elevated these rates of pedal errors. Overall, the laboratory data suggest that drivers do make foot placement errors, pressing the accelerator or the accelerator and brake, or slipping from the brake to the accelerator when the brake pedal was intended. That these errors occur at a relatively low rate, particularly among drivers who are experienced with their own vehicles—is consistent with the relatively low rate of unintended acceleration episodes reported.

FUNDAMENTAL PROCESSES IN MOVEMENT ERRORS

In this section some of the basic processes underlying these errors in movement which could lead to contact with the improper pedal are considered. Various writers in the field of movement control have found it useful to consider two separate classifications of such errors: errors in *response choice* and errors in *response execution* (e.g., Schmidt, 1976, 1988).

Errors in Response Choice

Response-choice errors, familiar to us all from everyday experiences, involve a clear decision among two or more alternatives with the incorrect choice being made occasionally (e.g., moving a lever up rather than down). Presumably the functionally highest levels in the central nervous system (involving consciousness) select which action to take in a given circumstance, and then the results of this decision are passed to functionally lower levels in the system (brainstem, spinal cord, etc.), resulting in spinal-level commands to the muscles concerning the amount and timing of forces that produce action (Schmidt, 1988). At first glance these errors in choice seem to be a basic cause of foot placement errors in driving: the driver for some reason occasionally "chooses" the accelerator pedal rather than the brake. However, in laboratory experiments involving speeded choice among alternatives in situations measured by choice reaction time, subjects make response-choice errors relatively frequently. The percentage of these errors varies widely with instructions and a host of other factors, but a rough estimate of the rate would be about 5% (e.g., Angel and Higgins, 1969; Schmidt and Gordon, 1977), which is far more frequent than the accident data suggest for unintended acceleration. In addition, errors are usually detected and corrected very quickly (Angel and Higgins, 1969; Rabbitt, 1967; Schmidt and Gordon, 1977; West, 1967), unlike the unintended acceleration episodes, in which no corrective actions are taken.

Viewed critically, this kind of error is probably not a major factor in unintended acceleration. It would appear from the accident reports that the driver has almost always made the correct conscious choice about which pedal should be pressed in shifting from Park to Drive or Reverse (the brake should be pressed). Indeed, the drivers express surprise—even indignation—when the suggestion is made that the accelerator pedal might have been pressed accidentally, as if they "chose" the wrong pedal consciously. Putting aside the possibility that the drivers are not being truthful in their statements, the laboratory data suggest that if a conscious error in response choice were made, the drivers would soon be aware of it and quickly initiate correction.

Errors in Response Execution

Even if the person has made the correct choice in movements (no error in response selection), quasi-random variability introduced during the many (often nonlinear) translations eventually leading to muscular contraction and movement results in variability in the trajectory generated in the limbs, which represents a second class of errors termed "response execution." This source of error can be seen in numerous common situations such as throwing a dart at a bull's-eye or shooting free throws in basketball. In the latter example, the conscious choice of what to do (make the basket) is constant from attempt to attempt. Yet even the most proficient players produce attempts that are variable from trial to trial. I conceptualize these errors as having the variability in the choice of the movement from response to response minimized, thus revealing a source of variability associated with the movement *production* as the major source of inaccuracy. These errors are thought to be caused by lower-level variability in unconscious processes that translate higher-level commands into forces and timing at the level of the musculature (e.g., Schmidt, Zelaznik, and Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, and Quinn, 1979).

Applying this to the problem of unintended acceleration, one can conceptualize the person as having made the correct decision as to which pedal to press, but variations in the lower levels in the system make the actual trajectory and endpoint of the foot movement variable, just as the trajectory of the arm shooting the basketball is variable. According to this model, almost every braking movement results in the foot making contact somewhere on the brake pedal, with considerable variation in actual placement allowed in the vehicle because the brake pedal and foot are relatively large and overlap considerably. Occasionally, however, the variations are so large that the brake pedal is missed completely. If this deviation is to the right, then the accelerator pedal is struck instead, even though the driver has fully intended to press the brake. As I will discuss later in this article, because the driver intends to press the brake and expects that his or her foot will do as instructed, this can lead to the perception (albeit false) that the foot was on the brake during an episode of unintended acceleration.

Response Execution Errors: Variability and Bias

Given an error in execution even when the proper response choice has been made, these errors have two main characteristics, or descriptors: variability and bias. Variability refers to dispersion around the mean movement direction, usually expressed as a *variable error*, or the within-subjects (over trials) standard deviation of the performer's responses about his or her own mean. However, at the same time, a performer can display a systematic bias measured by *constant error*. Such errors are usually relatively small, but they can be a source of overall performance error under certain circumstances, as discussed later. Research suggests that different factors are responsible for, or are causes of, variable and constant errors, and these two errors represent fundamentally different aspects of aiming accuracy. Of course, factors that increase either constant or variable errors can be expected to result in fewer target contacts in general, and thus both are relevant to this discussion (see Schmidt, 1988, chapter 3, for a review).

Sources of Variability in Human Aiming Movements

Aside from the arguments from the practical examples discussed earlier, what is the evidence for these lower-level sources of variability, and what are the factors that determine the nature and amount of such variability? This problem has been examined at my laboratory, where the subjects were asked to produce a series of simple, ballistic (uncorrected) static contractions of the elbow flexor muscles to exert force against a handle, attempting to achieve a particular amount of peak force on each trial. The amount of force was varied in different conditions, and Figure 1 shows that the within-subjects standard deviation (SD) of the forces produced (a variable error as defined earlier) was about 7% of the amount of force produced on average. Asking the performer to make a larger contraction results in systematically larger variability; this variability is roughly linearly related to the amount of force required up to about 65% of maximum (Schmidt, 1988). This feature holds for both static and dynamic contractions (Schmidt et al., 1979), and this variability represents a source of variability in lower-level processes in the spi-

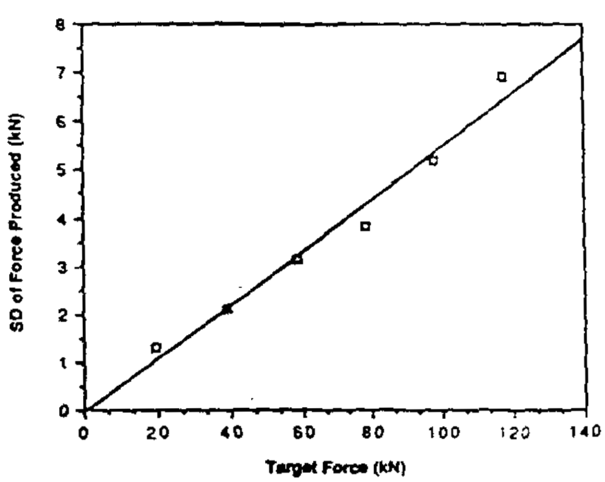

Figure 1. *Average within-subjects variability in forces produced in simple, uncorrected muscular contractions as a function of the level of force required (adapted from Schmidt et al., 1979).*

nal cord which cause a muscle to contract, or in the muscular contractile process itself (Schmidt, Sherwood, Zelaznik, and Leikind, 1985).

Another source of variability is the timing of these contractions within a movement, reflected as variability in the timing of the signals to the muscles from the spinal cord. To study this variability, subjects were asked to make simple back-and-forth movements of a lever in time to a metronome, and we measured the timing of the onset and offset of the force-impulses that were produced. Figure 2 shows the within-subjects standard deviations of the durations of these impulses for four different target impulse durations that were determined by the metronome settings. Variability in the muscular timing was about 5% of the duration to be timed, and this variability increased in nearly direct proportion to the overall duration of the movement. The four separate data points at each movement time are for different movement amplitudes, which had no systematic effect on the timing components of the variability. Thus we view the effect of altered force requirements and the effect of altered temporal requirements as having separate physiological mechanisms (Schmidt et al., 1979).

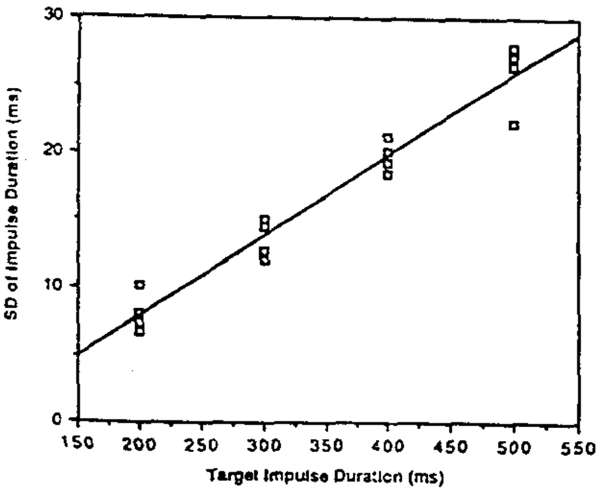

Figure 2. *Average within-subjects variability in the timing of muscular contractions in a reciprocal lever movement as a function of the instructed impulse duration (movement time) for each move. Different data points at each impulse duration are for different movement amplitudes, which had no reliable effect on timing errors (adapted from Schmidt et al., 1979).*

These findings have critical importance for understanding movement accuracy. The actual trajectories that result from running a motor program can be seen as influenced by the forces produced in the muscles during the action and the timing of these forces. Therefore any unintended variations in these processes "downstream" from the cognitive decision processes will result directly in variations in the trajectory of the movement and hence will result in variations in the location where the limb eventually comes to rest. Thus for movements such as aiming a foot at a pedal, the driver's motor system contributes several sources of error (one in force produced, another in timing) which tend to cause the limb to deviate in unpredictable ways from the position that the driver originally intended.

Role of movement amplitude. These sources of errors are not fixed in amount but vary strongly with several variables of the movements. One important variable is the movement distance. If the duration of a movement is held constant, then increasing the distance to be moved will require an increase in the level of forces produced in the movements. In Figure 1, however, we see that increasing the level of force increases the amount of variability in force produced. This increased muscular variability results in greater variability in the overall trajectory, as mentioned earlier. These effects can be seen in Figure 3, which illustrates the results when the subjects were asked to move a hand-held stylus various distances (from 10 to 30 cm) to a target with a quick movement. As the movement distance increased, the variable errors in hitting the target (here expressed as the average within-subjects SD of the movement amplitude) increased linearly.

The errors in aiming discussed here lie on a

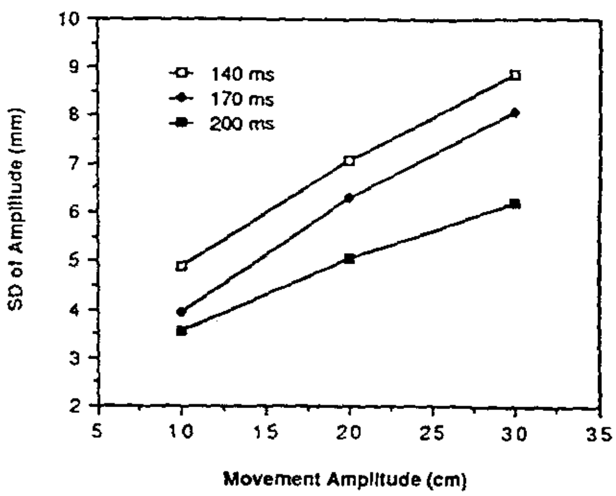

Figure 3. *Average within-subjects variability in movement amplitude in aiming a hand-held stylus at a target as a function of the required movement amplitude and movement time (adapted from Schmidt et al., 1979).*

dimension parallel to the direction of the movement, but this principle also applies to errors measured perpendicular to the movement's overall direction (Schmidt et al., 1979). Variabilities in the muscular contractions cause the movement to vary from its intended direction, and this process is heightened because the forces are larger when the movement is longer. In addition, when the movement is initially headed in the wrong direction, then the farther the limb travels at the wrong angle, the larger will be the size of an error when the limb finally reaches the target area (e.g., Schmidt et al., 1979). This is particularly relevant to aiming errors of the foot toward a pedal, as it is the variability in the lateral deviation of the foot which is likely to lead to the incorrect pedal being struck.

With regard to unintended acceleration, the farther the foot is from the intended pedal when the driver initiates movement toward it, the larger the variable errors in hitting the pedal will be. After the driving cycle has begun, and when the right foot is on the accelerator, the movement distance to the brake is relatively small—perhaps even with the trajectory being constrained by pivoting the right heel on the floor—and such variable errors would be considerably smaller. However, if the driver is about to initiate the driving cycle, the right foot could be in a variety of places prior to shifting from Park. Such foot positions are probably somewhat farther from the brake than if the foot were on the accelerator during the driving cycle, and the variable errors in aiming should be somewhat larger as a result. In addition, movement to a target from a consistent place (e.g., the accelerator pedal) that has been very well practiced is less variable than movement to that position from several less well defined places, each of which has not received as much practice. On various grounds, then, variable errors in aiming should be larger at the beginning of a driving cycle than after it has begun (see also the later section on postural set).

Role of movement time. Another important source of variability is the movement time. With movement distance held constant, moving faster will require increased forces to be produced, which should result in increased muscle variability and hence more variability in the actual trajectory of the limb in space. This effect can also be seen in Figure 3, where the movement time of the aiming responses has been varied in different conditions. As the movement time decreased, there was a systematic increase in the amount of variability in the aiming movements. The general relationship is that the variable errors in aiming are approximately proportional to the reciprocal of movement time: that is halving movement time essentially doubles the variable errors in aiming. The combined relationship of movement time (MT) and movement amplitude (A) is that variable errors are essentially proportional to the average movement *velocity*, or A/MT (Schmidt et al., 1979). Applied to the problem of unintended acceleration, other things being equal (e.g., initial foot placement), if the driver makes a faster movement to contact the brake pedal, then that movement would be more variable in reaching its goal. This could be relevant in various accident cases, particularly if the driver is rushed to make a braking response.

Movements in different limbs. Most of the research on sources of movement execution errors has been done using the upper limbs, and apparently no research dealing with this problem for foot/leg aiming has been conducted. However, there is no reason to suspect that the principles of foot/leg action would be substantially different from those found in the arms and fingers. Some research has been done comparing fingers, hands, and arms in tasks in which the subject had to aim a stylus horizontally at a target (e.g., Langolf, Chaffin, and Foulke, 1976). Here the relationships among distance, accuracy, and movement time were essentially similar among these various limbs, but there was systematically more slowing (because of increased variability in trajectory) as the size of the limbs increased. If this is carried further, one might expect that the variability in leg/foot aiming would be even greater than that for arm aiming. If so, then this evidence provides a basis for understanding foot placement errors in unintended acceleration.

Factors affecting movement speed. When a cold engine is started, several adjustments of fuel flow and mixture are designed to occur automatically to compensate for the engine temperature, a cold ambient temperature, or other factors, and these adjustments make the idle speed slightly higher than it would be if the car were warm. Under normal operation, cold idle speed with the transmission in Drive might be a few hundred revolutions per minute higher than when the vehicle is warm. These changes in idle speed in late-model vehicles are typically mediated by on-board computers, but analogous alterations in idle have been controlled via mechanical devices inherent in the automatic choke for several decades. This increased idle is clearly not sufficient per se to cause unintended acceleration: unchecked by braking, this high-idle condition would accelerate the vehicle very slowly, attaining asymptotic speeds of at most 24–32 km/h after 30 s. Any increased engine noise is slight and is certainly not startling. The situation can be thought of as routine because drivers are usually prepared for their vehicles to display a somewhat faster idle when cold.

However, when the driver shifts from Park to Drive or Reverse with this high idle, a slight shudder is felt as the vehicle begins to move, and this might be sufficient to cause the driver to initiate a somewhat faster foot movement toward the brake to halt or slow the vehicle's gradual movement. Being slightly faster, the movement would be expected to be somewhat more inaccurate as a result, as shown in Figure 3 for hand movements. If this error is sufficient that the accelerator is pressed instead of the (intended) brake, then the vehicle would increase acceleration, leading to further pressing of the "brake," leading to more acceleration, and so on, turning the normal cold-start situation into an unintended acceleration episode. This pattern is consistent with numerous accident reports in which the driver stated that the harder the "brake" was pressed, the faster the vehicle would go. This effect is made more probable at the start of a driving cycle, when slightly higher idle of the cold engine is coupled with the driver's potential seating biases (misalignments) immediately after entering the vehicle (see the following section for sources of such bias).

In a test of this account of unintended acceleration, Tomerlin (1988) instructed subjects to drive through a predetermined course set out with cones on a wide paved surface. In one part of the test the drivers were to back the test vehicle (not their own car) along a narrow, curved path. Just before this segment began, the on-board experimenter increased the idle speed unexpectedly. Of 130 subjects, two subjects produced episodes of unintended acceleration in which the vehicle accelerated maximally and had to be brought under control by the experimenter. In both cases the experimenter observed that the accelerator was pressed rather than the brake pedal, with both subjects believing that their right foot had been on the brake. In another experiment (Tomerlin and Vernoy, 1988), at the start of a similar backing action when the subject shifted from Park to Reverse, the experimenter unexpectedly moved a lever that depressed the accelerator *fully*. Of 169 subjects in this study, 1 demonstrated a clear pedal error whereby the driver fully depressed the accelerator rather than the brake and kept the right foot on the accelerator until the experimenter turned off the vehicle with a remote "kill" switch. The interpretation is that when the higher-idle situation was presented, it elicited a faster (and more variable) movement to the brake, causing the foot to miss the brake pedal and to contact the accelerator pedal on these few occasions.

These data are important for several reasons. Whereas these episodes of foot-placement errors were rare, occurring in only a small minority of subjects, these data provide unmistakable evidence that such errors *can* occur in normal, experienced drivers. The experiments describe first-hand observations of drivers fully pressing the accelerator when they intended to press the brake, with these errors being of sufficient duration to have caused an accident had the experimenter not intervened. Prior to Tomerlin's report, evidence for such foot placement errors in unintended acceleration was based only on retrospective statements of the drivers involved in an accident. These statements, although certainly suggestive of the actual events leading to the accident, are potentially biased in several ways and should be considered somewhat cautiously. However, Tomerlin's data remove doubt that such episodes can occur because of foot placement errors. Of course, episodes of unintended acceleration are quite rare given the large number of times that drivers generate brake-pedal movements during a year's driving without experiencing an accident. In this sense, that the incidence of foot placement errors was also very rare in Tomerlin's experiments is consistent with the frequency of such episodes generally. In fact, the rate of such episodes was somewhat higher in Tomerlin's experiments, perhaps because the drivers were generally unfamiliar with the particular test vehicle—a factor identified earlier as being relevant to unintended acceleration.

However, Tomerlin's data are not particularly strong in implicating high idle per se in unintended acceleration episodes. First, a high-idle condition was clearly not a sufficient condition to produce these errors, as all subjects but three (in two experiments) behaved appropriately when the idle speed was unexpectedly altered. Also, even for the subjects who did produce these foot placement errors, the idle had to be increased to extreme, unrealistic levels in order for errors to occur. (In Tomerlin and Vernoy [1988], recall that the accelerator was depressed fully by the experimenter.) Unfortunately, there was no normal-idle control condition used for comparison, so one cannot be certain that these errors would not have occurred in any case, independent of the idle conditions. Taking all the evidence together, it is reasonable to argue that the high idle might have generated a somewhat faster brake-pedal movement, leading to increased incidence of pedal errors on these few occasions; however, without records of the foot movements in these cases, it is difficult to be very confident.

Thus despite the tendency for these unintended acceleration episodes to occur in Tomerlin's conditions, it seems likely that the ultimate cause of the errors was low-level variability in the foot trajectory toward the brake, exaggerated somewhat because of slightly faster movement speeds. This variability as a source of pedal error can be enhanced by several other sources, such as various biases (or systematic shifts) in the aiming direction. These biases are discussed more fully in the following sections.

Sources of Bias in Human Aiming Movements

To this point I have considered lower-level processes that lead to variability about the mean movement direction in aiming movements. However, in unintended acceleration situations there is also the possibility that for one reason or another the driver has temporarily biased the direction of aim slightly rightward when starting the driving cycle. Usually this small bias will not create a problem, as the foot simply reaches the brake pedal slightly to the right of its usual location. But if this rightward bias is large on a particular instance, and/or it is compounded by a source of rightward variability, the result could be a movement that is exceptionally shifted to the right, sufficient that the accelerator is struck instead of the brake, leading to unintended acceleration. This section describes some of the sources of bias.

Head and body position. Generally factors that tend to cause biases in the seated position relative to the habitual straight-ahead position would be potential sources of bias in foot aiming. Of course, some bias may be produced simply because the head is physically connected to the foot via rigid links in the body segments. Thus when the head is turned to look over the right shoulder, as occurs when most drivers back up, the physical connection to the shoulders and hips could cause a rightward bias in the aim of the right foot. Another source of bias is the variability in the seating position experienced when driving is resumed, as if the subject's postural set or general orientation to the vehicle were disrupted (e.g., Nacson and Schmidt, 1971; Pepper and Herman, 1970; Schmidt and Stelmach, 1968). These losses in proficiency, though temporary, can be substantial for a few seconds and have been shown to produce large systematic biases in aiming. Related to unintended acceleration, when the driver returns to the car to begin a driving cycle, the lost postural set may result in an aiming bias that if directed to the right, could lead to the accelerator being pressed rather than the brake. Given that a pedal misapplication is not made at the start of the driving cycle, further driving would reduce these biases quickly, consistent with the relatively lower incidence of unintended acceleration once the driving cycle is well under way.

Head position and direction of gaze. Some recent experiments have shown that head and eye position can influence limb placement even when the limbs are not mechanically influenced. In one example Marteniuk and Roy (1983) asked subjects to position their hands at an unseen target, remove their hands, and then reposition them as accurately as possible after a short rest interval. During this interval the subjects were asked to move their heads to a new position 10–30 deg to the right or left of the original but with the direction of gaze fixed. In other experiments they asked subjects to move their direction of gaze 10–30 deg but with the head position fixed. The positions of the shoulders and trunk were rigidly controlled. Even though the subjects were not looking at the target toward which they were aiming (just as the driver does not usually look at the brake pedal), moving the head and/or eyes caused large, systematic biases in the direction of aiming. These ranged from a 5.7-deg error to the left when the head was rotated to the right, to a 4.6-deg error to the right when the head was rotated to the left. Control experiments showed that these biases are mainly caused by the position of the head and are relatively independent of the direction of gaze. Other control experiments in this series show that the effects occur even if the subject moves a pointer by rotating a knob, so that the effect is probably not caused by biases in the felt position of the arm. Rather, shifts in head position signaled by the receptors in the neck apparently alter the perceived spatial position of a target with respect to the body (see also Roll, Bard, and Paillard, 1986).

Related to unintended acceleration, this evidence suggests that the perceived spatial position of the unseen brake pedal could be strongly biased by head position. If the head is turned to the left, as it might be while looking in the left side mirror, reaching for the seat belt, or other, similar maneuvers in the initiation of the driving sequence, the result could be systematic biases to the right in the perceived position of the brake pedal. This bias could be as large as 6 cm in a driver of average height if the angular bias were 5 deg and would be sufficiently large that the driver could miss the brake altogether and strike the accelerator. Similar errors could be caused by looking to the right, which would bias the foot movements to the left, but these would not be particularly important as they would not usually result in a serious error. One should be cautious in interpreting this evidence, though, as the experiments involved hand movements rather than foot movements, were conducted in the dark where visual information from the environment was minimized, and involved slow positioning movements that are probably more consciously controlled than are foot movements in vehicles.

Role of vision and optical flow. In the past decade there has been increased understanding of the role of vision in movement control and posture, and this knowledge has the potential for accounting for several features in unintended acceleration. Gibson (1966) and Lee (1980; Lee and Young, 1985) argued that posture and locomotion as well as other actions are modulated by optical information created as the individual moves through a textured environment, generating continuously changing patterns termed the *optical flow*. The important point is that the pattern of optical flow is uniquely determined for each trajectory of the eye through the environment, allowing optical flow to specify the nature of the trajectory. When moving through an environment, the pattern of optical flow specifies the straight-ahead position as that direction for which the rate of change of the angles of light rays is zero, with movement through an environment being critical for optical flow variables to operate. Finally, there is evidence for two distinct but overlapping visual systems—a conscious, mainly foveal system for object identification termed *focal vision* and an unconscious, phylogentically older, peripheral-plus-focal system for movement control termed *ambient vision*. Some of these ideas are reviewed in Schmidt (1988).

This background work on vision can be related to unintended acceleration in several ways. First, before the start of the driving cycle, the vehicle is of course stopped and optical flow variables are not useful in allowing the driver to detect the straight-ahead position; thus the driver relies on static visual information to orient himself or herself with respect to the straight-ahead position. Aaron (1988) has suggested that under these conditions the driver may be particularly susceptible to visual features of the *static* visual surround that may bias the perception of the straight-ahead position and, hence, seating position. Should this bias be to the right, then the direction of a foot movement toward the brake might instead be directed rightward toward the accelerator. Aaron argued that in some vehicles static visual cues to the straight-ahead position (and hence the position of the brake) are diminished, as by obscuring the brake pedal from peripheral vision with package trays under the steering wheel or by a lack of distinguishing features such as a center hood ornament. In addition, several features might bias the driver rightward, such as a rightward placement of the steering column and instrument cluster with respect to the brake, a tipping of the plane of the steering wheel forward at the left, or sculptured edges on the hood (or seams) that curve toward the center of the vehicle. The importance of these factors would be expected to diminish after the start of the driving cycle, as the movement of the vehicle through the environment provides optical flow information that would specify the straight-ahead position, allowing the driver to become more effectively oriented in the vehicle. This might be relevant to understanding why these foot placement errors occur most frequently in a stationary vehicle.

Tomerlin and Vernoy (1988) have examined Aaron's (1988) views in studies estimating the extent of bias in the straight-ahead position in several different makes of vehicle. They found considerable biases in subjects' estimations of the straight-ahead position in static vehicle situations but no reliable between-make differences. However, even though subjects' perceptions of the straight-ahead position were biased, there was no correlation between this bias and any foot movement bias toward the brake pedal. It is possible that the detection of bias, being deliberate and necessarily based on conscious perception, used the focal visual system defined earlier, whereas the directional aiming of the foot movements used the (unconscious) ambient system that might not have been visually biased with respect to the perceived straight-ahead position. Evidence for such an assertion comes from recent experiments separating these two systems by Bridgeman, Kirch, and Sperling (1981). These are interesting possibilities for understanding unintended acceleration, but more study is required before one can be very confident about Aaron's hypotheses.

Negative transfer from other vehicles. A second factor that potentially can contribute to bias errors in foot placement is *negative transfer* from other vehicles. Generally defined as the decrement in the performance of one task as a result of practice or experience in some other task, negative transfer has been studied a great deal in both verbal and motor skills (see Adams [1987] and Schmidt and Young [1987] for reviews). It can be related to unintended acceleration in several ways, but perhaps the most obvious is with respect to the placement of the pedals in various vehicles with which the driver has had experience. There is a relatively narrow range of pedal placement configurations in various makes of automobiles, with the right edge of the brake and the left edge of the accelerator being separated by 5–10 cm and with the right edge of the brake pedal being approximately 1–2 cm to the right of the steering column (Roush and Rasmussen, 1974; Sursi and Mullins, 1984). Although these variations seem relatively small, if the majority of a person's driving experience has involved one brake pedal placement and then the person experiences another make of automobile in which the brake pedal is placed more leftward relative to the seating position, one could expect negative transfer from that person's prior driving experience to the pedal-striking accuracy in the new car. The aim would be systematically rightward of the pedal position, as if the person were actually in the earlier car. If this bias is overlaid with movement variability—as it always is in movement tasks—then a few of these movements might be expected to miss the brake pedal altogether, with the foot contacting the accelerator instead.

DETECTION OF ERRORS

The second major phenomenon to be explained in unintended acceleration concerns the common fact that the driver does not detect that the wrong pedal was contacted. Why, after the accident, is the driver typically convinced that the right foot had been on the brake when in many cases evidence showed that it was actually on the accelerator? These phenomena can be considered in relation to the processes leading to the detection of errors in motor actions, about which a considerable body of literature is available.

Intentional Responses and Efference Copy

I have argued that unintended acceleration occurs when the driver intends to move the foot to the brake pedal but initiates a movement that (for reasons discussed in earlier sections) does not reach its correct target. Here the functionally highest level in the system intends to produce a given response and has therefore made no error in choosing the brake pedal. However, variability and biases in the lower levels in the system, which actually carry out the movement, result in the intended movement occasionally going wrong. Current understanding of movement control in these rapid actions is that the higher levels of the central nervous system (CNS) pass control to the lower levels for execution, sometimes with feedback from the actual limbs being processed minimally, if at all. For these well-practiced and relatively simple foot movements, there is little need to check their intended outcomes for accuracy, and the system prefers an automatic mode of control that does not require attention. In such cases the higher levels simply allow the movement to run off (more or less as does a computer program) without much modification.

How, then, does the decision-making level of the system "know" where the limb is without processing feedback directly from it? When a command to make such a movement is given to the lower systems, the lower system will carry out this movement faithfully, as it has done many times in the past, and in this sense the higher level "knows" that the limb reached the brake pedal. The word "know" here is used in a special way, however. As an analogy, if I ask my secretary to telephone a message to my brother, I "know" he has received it even though I do not have access to the actual sensory data from the conversation. I expect my brother to be home at that particular time, and I can trust my reliable secretary to carry out my request. The situation is similar in the automobile: the driver has strong expectations about the location of the brake pedal and can "trust" the leg musculature to carry out the action as instructed. Then, after the movement has been initiated, the system "knows" that the foot has reached the brake pedal even though no feedback from the foot may have been involved.

Efference copy. This general idea has formed the basis for a number of theories of movement perception, usually coming under the label of "efference copy" or "corollary discharge" (e.g., Sperry, 1950; von Holst, 1954). These theories say that when a movement is produced and the efferent signal is sent, a copy of this efferent signal is also sent to sensory areas in the brain. This allows the highest levels in the nervous system to "know" that a movement has been commanded. More important, the efference copy provides a basis for "evaluating" the future movement, in that various checks can be performed on the efferent signal to detect whether or not the movement will be correct. If this analysis reveals that the movement is going to be incorrect, then this movement can be aborted and a corrective movement can be generated. This process is very rapid because the higher levels in the nervous system do not have to wait for the feedback to return from the moving limb in order to detect an error. Theories of efference copy for motor behavior are very interesting and compelling, and there is considerable neurological evidence indicating pathways in the brain between motor and sensory areas (Evarts, 1973).

In the case of unintended acceleration, because the highest levels have correctly ordered a movement toward the brake pedal, analysis of the efference copy indicates that the movement will be correct—that is, toward the brake pedal—even though the actual movement may occasionally deviate from this goal and contact the accelerator. This is an important point because these theories can explain why the driver "knows" that his foot was on the brake when in fact it may have contacted the accelerator instead. Also, if the driver "knows" that the foot is on the brake, it explains why he or she presses the accelerator pedal harder when the car accelerates unexpectedly.

Selective attention and consciousness. The situation in which the driver does not "know" that the foot has made an error in execution can be thought about from other viewpoints as well. Attention (and awareness) is generally regarded as limited and serial in nature, and a *selective attention* process is thought to choose among those sensory data that are most relevant to the situation at a particular moment. Through selective attention, awareness can be attracted by suddenly presented and loud stimuli (noises, or intense stimuli from the body), which of course blocks the awareness of other events that may have been relevant previously. Reviews of these ideas have been provided by Keele (1986) and Neumann (1984, 1987).

One can also use these ideas to appreciate how a driver can make an error in foot placement and yet not detect it. For these foot actions little or no attention will be directed at the execution of the movement itself, particularly if it is fast, environmentally predictable, and well practiced, as these behaviors typically are (Posner and Keele, 1969; Schmidt, 1988). Once these foot movements have been initiated and the lower levels in the CNS assume control, selective attention directs attention to other sources of stimulation that will soon become most relevant, such as the visual array of traffic ahead of the car, planning and executing movements of the limbs for steering, and a host of other events. Roush and Rasmussen (1974) have reported that drivers typically move the right foot toward the accelerator simultaneously with movements of the shift lever, so that attention must be further divided between feedback from the hand, foot, and vision of the roadway, making it more likely that the relatively stereotyped foot movements would be ignored. For these various reasons attention is directed away from the feedback from the foot, making it more likely that the driver would not detect that the foot was on the wrong pedal if an error should occur. Because the driver has not attended to feedback from the foot indicating an error, the subjective experience is that the foot was on the brake pedal all along.

However, when the foot strikes the accelerator rather than the brake, should not the unexpectedly compliant dynamic feel of the accelerator compared with the expected feel of the brake, as well as its difference in position, be sufficient to alert the driver that the foot was on the wrong pedal? Unexpected stimuli of this general type could, under certain conditions, attract attention—and apparently they do in those cases in which we catch ourselves making this error. For these stimuli to be detected reliably, however, they need to be intense relative to the other simultaneous stimuli (Keele, 1986; Posner, 1978). In those cases in which the car accelerates unexpectedly, the sensation from the moving vehicle could be sufficiently intense that attention would be attracted toward steering and away from the foot. Perhaps this is one reason that the subjects who made foot placement errors in Rogers and Wierwille's (1988) and Tomerlin and Vernoy's (1988, static test) studies detected their errors and corrected them immediately, given that no acceleration cues were available from the static vehicles used.

CORRECTION OF ERRORS

Under many laboratory and practical conditions, errors in limb aiming can be detected very quickly (Angel and Higgins, 1969; Schmidt and Gordon, 1977). Of course, values for the latencies of such corrections vary widely depending on the subject's instructions and a host of situational variables, but there is evidence of corrections with latencies of 120 ms if the stimulus is kinesthetic, or approximately 200 ms if the stimulus is visual or auditory (Schmidt, 1988). Reaction times to initiate the foot movement toward the brake in simulated braking situations are somewhere around 500 ms, with another 100–200 ms for the movement of the foot from the accelerator to the brake. How, then, can one understand numerous cases of unintended acceleration in which the episode persisted for an order of magnitude longer than this—as long as 12 s in some cases? This section deals with some of the variables that would extend error correction times in these situations.

Persistence of Foot Placement Errors: Evidence

Various sets of accident reports, as well as several cases on which I was involved as an expert witness, provide ample evidence of the persistence of these errors. In the 1982–1983 accident reports from North Carolina, the statements of several drivers indicate corrective processes with very long latencies. After (admittedly) striking the accelerator rather than the brake, one driver entered an aircraft parking lot, struck another car, passed through a fence, and nearly struck an airplane; another driver went through a fence and continued through a field and into a creek; and another driver left the highway and traveled 38 m down the shoulder and through a parking lot, striking three parked cars before coming to rest. In all these cases the driver admitted that he or she continued to press the accelerator and failed to apply the brakes for a surprisingly long travel distance. It is difficult to ascertain the durations of these episodes, but it seems clear that had effective evasive action been taken sooner, the accident would have been much less serious than it was.

Hypervigilant Reactions—Panic

Probably the most effective way to understand this persistence is through the concept of *hypervigilance,* more commonly known as panic. This term was coined by Janis and Mann (1977; see also Janis, Defares, and Grossman, 1983, for a review) after studying numerous situations involving extreme stress reactions, such as wartime settings, earthquakes, bombings, fires, and similar disasters, as well as others studied in the laboratory. According to their analysis, the reaction to extreme threat is one of "panic or near panic . . . characterized by indiscriminate attention to all sorts of minor and major threat cues as the person frantically searches for a means of escaping from the anticipated danger" (Janis et al., 1983, p.2) Other features are a temporary impairment of cognitive functioning and defective decision making, with much vacillation among alternatives. This behavior is followed by an impulsive choice of a hastily contrived solution to the problem that promises to be effective but which on later reflection was not effective and may even have been dangerous.

This hypervigilant state is sometimes also accompanied by the person freezing, apparently failing to take any action at all. More properly, however, the overt behavior of the individual may be to take no effective action, but the internal information processes are extremely occupied and overloaded. The high stress leads to excessive vacillation, with the person first attending to one cue, then another and then back again without ever initiating an effective response. This feature of responding is referred to as *distractability* (e.g., Easterbrook, 1959; Kahneman, 1973): various environmental cues attract attention in rapid succession. At the same time, the attentional processes are highly focused on whatever the person is attending to at the moment, and other effective cues in the environment are missed and not attended (see the section on perceptual narrowing later in this article). The person suffers a loss in immediate memory capacity (or span), which helps to account for the vague memories of accident-related events by drivers in unintended acceleration episodes. In addition, subjects engage in extremely simplistic thinking and reasoning (Beier, 1951; Berkun, Bialek, Kern, and Yagi, 1962; Kelly, Condry, Dahlke, and Hill, 1965) and experience disruptions in movement control, with the motor activity becoming more primitive and less sophisticated (Weinberg and Hunt, 1976; Weinberg and Ragan, 1978), together with strong emotional reactions (Fenz and Jones, 1972).

Janis and Mann (1977) mention three precipitating causes of the hypervigilant state, all of which seem to be present in unintended acceleration. First, there is a strong, startling stimulus, such as the shaking of a building in an earthquake or the sight of an enemy attack; in the automobile this would be the unexpected, violent acceleration and loud sounds. Second, this sudden stimulus information is perceived as being life threatening; in the automobile, this takes the form of fear for oneself, passengers, or pedestrians. Third, and perhaps most important, there is the perception that unless a solution is found quickly, serious consequences will soon occur. Time is running out rapidly in the automobile, and the rapid and continuing increase in speed, with the danger increasing every second, make continued inactivity progressively more serious and finding a solution ever more critical.

One view of the persistence of unintended acceleration episodes, then, rests on this relatively well-documented concept of hypervigilance. The acceleration startles the driver; it is life threatening; and time for a solution is short. Under such conditions information-processing activities are seriously impaired, effective solutions are not considered long enough for them to have an effect, the driver is distracted by a wide variety of events in the immediate environment, and often no effective action is taken until the accident occurs. The drivers in several accident reports stated that they just "froze," which would be consistent with this account. And as discussed earlier, the solution of removing the foot from the brake is not attempted, perhaps because the driver "knows" that the foot is on the brake. The subjective impression is that the brakes have failed and that the car is not under the driver's control, which adds to the driver's stress. In this state other solutions are not even attempted, such as switching off the ignition, applying the hand brake, or moving the shift lever to Neutral or Park.

Perceptual Narrowing

A related line of thinking about stress and human performance has involved the literature on perceptual narrowing. One effect of stress involves the shrinking of the perceptual field, as if the attentional focus is narrowed (or focused) toward highly relevant events. This is usually thought of as a reduction in the ability to deal effectively with relatively unlikely peripheral events in favor of focusing on more likely central events. The idea applies not only to visual stimulation but can be extended to all of the perceptual modalities (e.g., touch, audition). Weltman and Egstrom's (1966) data showed this effect clearly with novice deep-sea divers. Both peripheral and central visual stimuli were presented and reaction times to them measured on land, in a shallow swimming pool, or in the ocean at a potentially dangerous depth. Although there was nearly no change in the reaction to the central stimulus across these conditions, the reactions to peripheral stimuli were systematically slowed and even missed as the more threatening (deep-sea) conditions were presented. Thus stress involved the systematic shrinking of the visual field available for signal detection.

Easterbrook (1959) has used many of these ideas in a theory of cue utilization under stress. This view has strong relevance to the persistence of unintended acceleration discussed here and is remarkably consistent with the view of hypervigilance proposed by Janis and Mann (1977). In both views the information-processing activities are impaired because of ineffective cue utilization, there is increased distractability and vacillation between potential solutions, and some effective solutions are missed because of the narrowness of focus imposed by the stress.

Habitual Responses under Stress

Curry (1975) argued that many automobile accidents are caused by negative transfer from movement patterns that have become habitual through practice. In the usual case these habitual, well-practiced responses to stimuli are very appropriate, are not particularly attention demanding, and serve the driver well in everyday driving. However, under stress or startle associated with having the vehicle accelerate unexpectedly (because the foot was placed on the accelerator rather than the brake, as argued earlier), the driver is suddenly placed under high demand for effective action, and habitual responses such as hard braking may be generated when other movements would have been more adaptive (Gielen, Schmidt, and van den Heuvel, 1983). Of course, hard "braking" when the right foot is actually on the accelerator instead only generates more acceleration, more stress, more hard "braking," and so on. Regression to these relatively primitive levels of activity has been postulated in relation to the progression-regression hypothesis, evidence for which has been presented recently by Jagacinski and Hah (1988).

Accident data. In the 1982–1983 North Carolina accident reports discussed earlier, several of the drivers admitted a pattern of action that supports Curry's views. For example, in one case the driver fell asleep and was startled when the vehicle struck a curb; his reaction was to press the accelerator instead of the brake. Another report stated that as the driver "gave her vehicle gas while turning right, her vehicle accelerated rapidly . . . [and] she hit the gas again," resulting in an accident; in this case the startle from the unexpectedly high rate of acceleration probably resulted in a pedal-pressing response, but to the accelerator rather than to the brake. If hurried, these movements are likely to have larger variable errors (Figure 3), leading to even greater probabilities of missing the brake pedal. Although these reactions are probably not very common, the evidence suggests that they do occur under certain circumstances. Something similar to this pattern of action could account for at least some cases of unintended acceleration

SUMMARY

The phenomenon of unintended acceleration has not been systematically linked to any known mechanical or design defect in the involved vehicles. However, analysis of the research literature in human factors, experimental psychology, and kinesiology supports the view that these problems are caused by drivers producing foot placement errors, with some of these errors actually being observed in experimental driving situations. These errors mainly originate at functionally low levels of the CNS because of force and time variability in the spinal cord and in the muscles that produce the actions. Errors in conscious choice are therefore rarely involved, which is consistent with the fact that the drivers are frequently not aware of their errors in foot placement. Various factors, such as increased distance of foot travel and decreased travel time, systematically increase variable errors in placement. Systematic biases in aiming direction can result from changes in head position and from experience in other vehicles with slightly different pedal arrangements.

Once unintended acceleration is initiated, a serious contributing factor is the failure to detect and correct the foot placement error, mainly because of lack of effective feedback processing from the well-learned, essentially automatic foot movements. The onset of the unintended acceleration may produce a startle reaction compounded by severe time stress, placing the individual in a state of hypervigilance in which information-processing activities necessary to take effective action are seriously disrupted. Overall the literature is reasonably consistent in supporting the hypothesis of foot placement errors as the major cause of unintended acceleration.

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