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Final Report

Improving the Ability of Drivers to Avoid Collisions with Snowplows in Fog and Snow

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16. Abstract (Limit: 200 words)

The goal of this work is to understand how the processing of motion under the conditions created by blowing snow causes drivers to fail to detect that they are approaching a vehicle ahead. Color was examined under blowing snow conditions to assess whether an equiluminant (equal brightness) situation was created. In this situation, contrast in light level is not detected but differences in color are. When an equilument situation is created by snow, a perceptual illusion lowers the ability to perceive approach. The results indicate that colors in the red-yellow part of the spectrum can create a dangerous equiluminant situation in blowing snow and fog. We were unable to find an optimum color to paint snowplows to make them less susceptible to rear-end collisions.

Perception studies investigated the ability of the visual system to detect the expansion pattern that drivers use to perceive that they are approaching a vehicle. We found that low contrast created by a snow cloud greatly reduces the ability to perceive approach. Flashing lights that increase conspicuity, substantially decreased the chances that a driver will be able to avoid a crash. Additional ways to improve the placement of warning lights based on these findings were proposed.

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Improving the Ability of Drivers to Avoid Collisions with Snowplows in Fog and Snow

Final Report

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EXECUTIVE SUMMARY

The purpose of this work is to understand how the processing of motion under the conditions created by blowing snow causes drivers to not perceive that they are approaching a vehicle that they are following. The ultimate goal is to use this knowledge to propose methods for lighting and coloring snowplows that will reduce rear end collisions.

Under normal driving conditions, it is the expansion of the image of the vehicle ahead that drivers use to know that they are approaching it. We have found that blowing snow and fog can create conditions that impact the perception of expansion in a particularly insidious manner. A driver can clearly see the vehicle ahead but cannot sense expansion and therefore cannot sense their own approach -- leading them to the dangerously wrong conclusion that they are safely following at a constant distance and at the same speed as the vehicle ahead of them.

In this report, the ability of drivers to sense expansion is examined in two distinct but highly related ways. First, color was examined under blowing snow and fog with the intent of assessing their chances of creating an equiluminant condition -- a perceptual illusion that greatly lowers the ability to perceive expansion. Second, in the laboratory, we measured the impact of contrast and flashing lights (like those on a snowplow) on the ability of a person to perceive expansion.

The results of this work indicate that colors in the red-yellow spectrum can create a dangerous equiluminant situation in blowing snow and fog. We were not able to find an optimum color to paint a snowplow to make them less susceptible to rear-end collisions.

The perception studies investigated the ability of the visual system to detect the expansion pattern that drivers use to know that they are approaching a vehicle that is ahead. The research found that the condition created by a snow cloud greatly reduces the ability to pick up that information.

Effort is needed to develop lighting techniques that enhances the luminance contrast of lighting on the rear of snowplows.

Flashing lights that increase the conspicuity of a snowplow substantially decrease the chances that a driver will perceive that a crash is imminent. If only one kind of lighting were used, steady burning lights would be preferable to flashing lights. The goals of making the snowplow conspicuous and of improving the ability of drivers to perceive approach could both be maximized if both kinds of lighting were combined. To minimize interference effects flashing lights should not be excessively bright and should be placed so that they do not reduce the visibility of steady burning lights. For example, steady burning light bars could be positioned on the sides of the snowplow and a flashing light could be placed above the center of the rear of the snowplow.

An analysis of the information that specifies approach suggests that high contrast steady burning lights should be placed as far from the center and on the left and right sides of the rear of the snowplow.

Finally, efforts are needed to insure that this lighting does not become covered with a layer of snow and become invisible.

Because our visual system is wired to perform detection and motion perception in two distinctly different ways, we found that enhancing those aspects of a vehicle to make it more detectible at the same time makes the motion of that vehicle harder to perceive. Inadvertently, by trying to make the snowplow more detectible and therefore safer, we may have instead made it more dangerous for the driver following a snowplow in a snowstorm.

CHAPTER 1

1.1 Introduction and Research Approach

In a 2002 news release, the Minnesota Department of Transportation reported that there were an average of 110 crashes involving snowplows every year in Minnesota, injuring an average of 10 people annually (1). About 70 percent of all accidents involving snowplows involve collisions into the rear of snowplow trucks (2). Snowplows are a significant hazard for motorists driving on a road that is being plowed. These rear-end collisions do not seem to be due to slick roads. Instead they seem to be a result of a combination of moving faster than the driver senses, inability to detect hazards in the road ahead, and difficulty responding appropriately to detected hazards. A similar situation appears to occur under conditions of fog.

At the core of this work is the idea that blowing snow and fog create a perceptual environment which is different than other hazardous driving conditions. It is not simply that things are harder to see. Under these conditions, a driver may not be able to perceive their own relative motion or the relative location of things around them. This is a much more dangerous situation.

The important contribution of this research is the discovery that the visual information that optimally alerts a driver to the presence of a snowplow ahead is different from the visual information needed to know that one is approaching a snowplow and how one must maneuver to avoid a crash.

We have found, and this will be repeated throughout this report, that those steps taken to increase the conspicuity of a snowplow decrease the ability of a driver to perceive and avoid an imminent crash. This statement may seem illogical until one understands that in the human vision system detection is processed differently than motion and space perception. This has a direct influence on driving performance. If when we detect the flashing lights of an emergency vehicle behind us, our task (the job we must perform) is to pull over and stop the vehicle. This is an excellent task for detection. On the other hand, if we detect the orange bulk and blinking lights of a snowplow ahead of us, our task is to follow at a safe distance. This is not a good task for detection. In this case we need to enhance the perceptual information relative motion and relative distance.

The purpose of this work is to reduce crashes in conditions of blowing snow by understanding how drivers normally keep a constant distance ahead and to use that understanding to propose changes in the design of snowplow color and lighting. The understanding and implementation can be used to increase safety. The problem that this work addresses is also central to reducing rear end crashes under conditions of fog.

1.2 Research Approach

This report is separated into two main sections. The first section is primarily concerned with color. The second section is primarily concerned with measuring perceptual performance.
The goal of the color section is to determine the impact snow and fog have on the perceived color contrasts and to use this information to find an optimal color to paint snowplows. To do

this, patches of color were measured under a variety of winter weather conditions. The raw data was analyzed in two ways. First, the direct measurements were processed and evaluated for the likelihood that they would create dangerous perceptual conditions. The second part of the analysis used the measured data to try to create a mathematical model of the perceptual impact of snow and fog. The mathematical model could be used to find a theoretical optimal color for a snowplow that would improve safety.

The goal of the perceptual performance section is to measure a person's ability to sense motion information crucial for maintaining a safe distance from the rear of a snowplow. It reports on several experiments measuring the impact of lighting on an individual's ability to sense relative expansion and contraction motion. Expansion and contraction motion provides an answer to the question: Am I getting closer or farther from the rear end of the snowplow? This is crucial for safe driving.

CHAPTER 2
Color

2.1 Introduction

2.1.1 Color Measurement Analysis

Our work in the past has shown that under fog and blowing snow a dangerous equiluminant situation may occur for drivers who are following the orange snowplow trucks. An equiluminant situation occurs when the foreground perceptual luminant energy (i.e. brightness) is equal to the background luminant energy. When this happens, all of the information about the world is carried by color contrast alone and is processed in a different way by our perceptual systems. In an equiluminant situation, a driver approaching a truck from behind can clearly see the truck but cannot tell how fast they are approaching or exactly where the truck is positioned relative to themselves. This is due to color.

Past work found that the color Minnesota snowplows are currently painted (orange) creates an equiluminant situation under fog and blowing snow. The color actually seems to enhance this illusion. This work also found that the green of the trees, although they start at a lower contrast under good weather conditions, did not fall into the same dangerous perceptual illusion under blowing snow and fog conditions.

In the work presented in this section, different color patches are measured under a variety of weather conditions with the intent of finding an optimum color to paint snowplows. The work is split into three sections: measurements, direct analysis, and model construction. The overall analysis was not sufficient to find an optimum paint color but it does supply some rough color guidelines and illuminates the necessary criteria for construction of a complete model of how fog and blowing snow impact perceptual chromatic contrasts.

2.1.2 Why does the problem occur?

We have stated before (and our experience continues to support) the scenario which has us choosing exactly the color which maximizes the probability of creating an equiluminant situation in fog and blowing snow. The effect of equiluminance shows up as an inability to accurately determine distance and motion.

Every part of an image that impinges on our retinas is processed in multiple ways, simultaneously by our eyes and visual cortex. For the work presented in this report, the greatest concern of this analysis is between the strength of the information flowing in the luminance (or achromatic) channel and the two chromatic channels (Red/Green chromatic and Blue/Yellow chromatic channels). The amount of energy in the channels (or pathways) are defined by the relative contrasts in the image projected onto the retina and the way our own photoreceptors and neural pathways are wired up to process the information.

Distance and motion are apparently perceived most accurately through the luminance channel. The chromatic channels, which are poor perceivers of space and motion, are extremely good at detection (3). In other words, if we are in an equiluminant situation we can detect the object first – we just don't know where it is or how fast it is approaching.

When a color had to be chosen to paint the snowplows, an obvious way of doing this is to show a group of people a variety of colors under blowing snow conditions and ask them which one they see the best. The color which ranks as the one most people "see" the best would be the one used to paint the snowplows. An experiment set up this way is a classic detection task. This task would unfortunately choose exactly the color that promotes chromatic information over luminance information creating susceptibility for a dangerous equiluminant illusion. What is truly desired is to find a color that results in good detection and no equiluminant illusion. Then when a motorist is approaching the rear end of a snowplow, they can tell where it is and how fast they are approaching at the same moment they first detect it.

2.2 Measurements

2.2.1 Background

The data was captured by a chromaphotometer -- a machine that measures a color patch and responds with three numbers roughly corresponding to the intensity of the reflected light along the most perceptually salient averaged spectra. In other words, the chromaphotometer measures color. People are not machines. Our perceptual system is complicated, dynamic, and fluid. When the ambient lights are bright, our pupils contract making the image on our retina dimmer. When there is little light available, we switch from perceiving with the cone photoreceptors to perceiving with the rod photoreceptors. Our photoreceptors are constructed facing the back of the retina which means that the neurons carrying their information to the brain must be pulled through the retina creating a blindspot in our visual field. The information from the retina is folded and compressed before it is transferred to the visual cortex in evermore complex ways which results in our being much more sensitive to relative changes than absolute changes -- especially color, where we can change the color of a grey patch dramatically simply by changing the color of the background upon which it is displayed.

These are only a few of the functions that our own eyes perform on the images impinging on them. Our eyes perform these functions so fluidly, effortlessly, and with such confidence building accuracy that we are blind to the complexity of our own perception. On those rare exceptions when the world is not performing as our eyes tell us, we are truly astonished -- sometimes denying the possibility of a weakness in our perception in favor of an external magical force. Vision is magic.

The goal is to find a color to paint a snowplow which increases power in the luminance channel while it reduces the power of the chromatic channels especially when they are driving in blowing snow.

2.2.2 Method

Several colors were painted with flat enamel paint on an aluminum panel. The colors were black, white, green, red, blue, and yellow. This was mounted thirty feet from the measuring point. These were used as the foreground colors. A neutral grey aspen tree, an evergreen tree, and a point in the snow, all fifty feet away from the measuring point, were used as background colors.

The measurements were taken in Duluth, Minnesota over the winter months from December 2004 to march 2005. The measurements were all taken late morning or early afternoon in daylight conditions under a variety of weather conditions. These conditions were labeled overcast, snowing, or fog conditions. There were a total of eight days that were measured during the winter.

The measurements were taken with a Minolta Chromaphotometer. The readings were given in the form of CIE (Commission Internationale de l'Eclairage) coordinates (a standard system that characterizes colors by luminance parameters by specifying a point on the chromaticity diagram) which were changed to candelas/meter squared (candelas are a basic unit for measuring light intensity) and then rotated to conform with the colors produced by the phosphors on the computer monitor. The color coordinates of the computer monitor were chosen so that they could be compared with computer generated simulations performed at a later time.

Each data point was normalized with respect to the white color patch in the scene. This amounts to white balancing the data. This process means that each data point then lies between [0,1]. A value of [1,1,1] for R,G,B (Red- long wavelength light, Green- middle wavelength light , Blue- short wavelength light) results in white.

After white balancing, the normalized contrast of the data point with the background neutral grey was found. This was done by differencing the coefficient of the measured color patch with the coefficient of the neutral grey. This gives a color value relative to a grey background. These coefficients were used to calculate the perceived channel energies. The perceived channel energies are a perceptual measure and will be described in more detail below.

2.2.3 Perceptual Complexities

Luminance or brightness energy is processed by a channel or pathway in the brain that does not distinguish between the colors of the light that stimulates it. The luminance channel is also referred to as the achromatic channel because it sums the output of the color sensitive cones in the retina. The chromatic channel uses the differences between the outputs of the color sensitive cones in the retina.

The first problem confronting the analysis of is that there are many individual differences in our visual perception. These differences show up in both how we sense colors (i.e. colorblindness) and how we process those colors into our perception (i.e. equiluminant motion perception). This analysis assumes an ideal color perceiver – a person whose perceptions is based on an average performance. True performance may vary for any given individual.

Another analysis difficulty is the non-linear way our luminance and chromatic channels are formed. Let the response of the cones at a point on our retina be represented by R, G, and B (these are the normalized measurement of a color patch at a given moment in time). Then the luminance and chromatic channel information are found in the following set of equations:

1) Lum = R + G   luminance channel

2) R/G = R – G   red/green chromatic channel

3) B/Y = B – (R+G)/2   blue/yellow chromatic channel

Notice that the luminance channel is part of the B/Y chromatic channel. This means that in an absolute sense, increasing the power of the luminance channel could increase the power of the chromatic channel at the same time-- resulting in no reduction of the equluminant illusion.

A third problem from the point of view of analysis is that information is sensed in contrast. In other words, it is not just the color of the truck but also the color of the background which is important. Boundaries are critical.

A final problem which we must keep in mind is that our vision is a dynamic process and can subtly change as our task changes. The measurements we take with the photometer are not dynamic and rely only on the external light energies and not with any history.

Our job in the analysis is to move from the measured values in the environment to an estimate of the power of the energy transferred along each of the perceptually defined channels. We need to characterize what blowing snow and fog do to the perceived contrasts. With that characterization we can estimate the impact on our ability to perceive motion and space.

2.3 Direct Analysis

This data in the Table 2.1 below was calculated from the raw data. Each value was obtained by first balancing for white, the calculating: 1. The contrast with respect to grey, and 2. The average channel energy level. The values reported here are the average chromatic channel energy divided by the luminance channel energy as shown in equation 4. This is a measure of the relative power of the information along each perceptual channel. Numbers above one indicate that these colors create an equiluminant situation.

4) NSR = (|R/G| +|B/Y|)/|Lum| Noise to Signal Ratio

Table 2.1 Channel Noise to Signal Ratio (NSR)

	OVERCAST	SNOW	FOG
Black	0.129426	0.124209	0.096784
White	0.040577	0.07646	0.207805
Red	**1.162538**	**8.405142**	0.802895
Green	**19.68379**	0.284826	0.578497
Blue	**3.19489**	**1.522097**	**3.592568**
Yellow	0.307224	0.54444	**1.140264**

Values indicating an equiluminant situation in **Bold**

The green patch on the overcast day shows a whopping 19.7 on its Noise to Signal Ratio (NSR, the relative energy level of the background to that of the central object of interest). Examining the data more closely shows that the flat green color happens to be equiluminant with respect to the background grey. This is simply a lucky (or rather unlucky) accident. Notice that although it is equiluminant under normal overcast conditions, the addition of snow or fog dramatically improves the performance criteria. A closer examination of the data shows that under snow and fog conditions there is an addition of a red component which is sufficient to push the green patch out of its equiluminant balance with the grey. It actually shifts the amount of the red component contrast from a negative to positive value.

The blue patch on the overcast day is also in equiluminance with the grey background. Unlike the green patch, the blue basically stays equiluminant under all the weather conditions. In this case, the blue patch shows a relatively low luminance energy contrast with respect to the grey background. Its chromatic contrasts are dominated by the blue component of its color which feeds directly through to the energy of the blue/yellow chromatic channel.

The red patch begins in a mildly equiluminant situation but under snow conditions it is highly equiluminant. When we look into the data we find that in snow the luminance channel energy decreases while at the same time the energy in the red/green chromatic channel increases. The amount of blue component stays roughly the same for the red patch but the decrease in the luminance channel energy has the additional effect of increasing the energy in the blue/yellow channel. The result is a dangerous equiluminant situation.

The same does not seem to occur in fog. In both fog and snow the red contrast is decreased (gets closer to zero) and the green contrast gets more negative (as if more green were being added to the background. In the snow condition it results in an equiluminant situation. In fog it results in only a marginally equiluminant situation.

The yellow patch seems to be effected differently than the red patch by the snow and fog. The yellow patch was not equiluminant either in overcast or snow conditions. In fog it did become equiluminant with the grey patch.

2.3.1 Summary of Results

In Table 2.1, a number greater than one indicates an equiluminant situation. Both became equiluminant under worsening weather conditions. The red patch becomes equiluminant in snow conditions. The yellow patch becomes equiluminant in fog conditions. We speculate that the orange is probably bad under both conditions.

The blue patch was equiluminant for all of the conditions. It had a low relative luminance contrast and a dominant blue component. This meant that there was always a significant amount of energy in the blue/yellow chromatic pathway under all conditions.

The green patch was an anomaly. On an overcast day the green patch was equiluminant with the grey background. Under snow and fog conditions it became strongly luminant. This indicates that the green under most conditions would be strongly luminant especially if the background shifted in color slightly.

This brings us to a critical point. Color is sensed relative to its surroundings. A better measure of the background would give us a better analysis.

2.4 Model Construction

The following section outlines three different models of the action of snow and fog on the perceptual chromatic contrasts. A good model of the impact of blowing snow and fog on the contrast’s energies is necessary to find an optimal color for a snowplow. The results below show that the necessary model is more complex than initially conceived. All of the models presented below use measured values to extract the underlying components of the snow and fog on perceptual contrasts. Other measured data is used to evaluate how well these extracted components model reality. This is a classic method used in pattern recognition to get at the underlying mathematical description of an unknown machine process (4).

2.4.1 Simple model of snow and fog on color measurements.

In the simplest model of the impact of snow and fog on our perception of motion we assumed that the bad weather would have a multiplicative effect on the color. Another way of saying this is that snow and fog act like a colored lens over our eyes.

In this case for each color measured, three values for the channel energies are shown by the equations below:

5) $Lum = k*R + l*G$

6) $R/G = k*R – l*G$

7) $B/Y = m*B – (k*R+l*G)/2$

Where k,l,m are the filter coefficients of fog and snow given by:

8) $k = R(s)/R(o)$, $l = G(s)/G(o)$, $m = B(s)/B(o)$

R(s),G(s),B(s) are chromatic values under snow conditions
R(o),G(o),B(o) are chromatic values under overcast conditions

If the fog and blowing snow were acting as a simple filter, the coefficients would be similar for all the colors we measured at a given time. The value of k, l, and m extracted from a patch of red paint would match the k, l, and m values extracted from a patch of yellow paint for a given intensity of snow or fog. This was not the case from the measured data shown in Table 2.2.

Table 2.2 Average Values of k,l,m Estimated from Data

	k	l	m
Red	0.682472	2.144908	8.317693
Green	-0.19962	1.167832	1.153456
Blue	2.421229	-2.26778	0.74189
Yellow	2.372236	-2.51783	24.09047

2.4.2 Incorporating residuals

A second model of the impact of blowing snow and fog on chromatic contrast and therefore the perception of motion, tries to explicitly incorporate the residuals of the simple model. Physically, this makes sense because for instance, snow is not just a filter. The particle of snow is between the viewer and the object being viewed. Its motion and its structure will lend it some filter-like effect but it will also contribute its own color to the overall average measurement of the color. The snowflake or fog particle obscures a speck of the object being viewed and in its place contributes a small bit of white. This assumes that snow or fog influence the foreground and background equally.

This model can be captured in the following measurements and assumptions. The channel energies are modified by the addition of three new variables. The resulting equations are shown below:

9) R(s) = k(1)*R(o) + k(0)

10) G(s) = l(1)*G(o) + l(0)

11) B(s) = m(1)*B(o) + m(1)

We again assume that the coefficients are constants for a given intensity of snow. This means that these coefficients can be extracted by using the measurements from two different colors taken at the same time. If this model captures most of the impact we could extract their values from three different color patches grouped in combinations of two. The extracted values should be similar.

This again is not the case as can be seen from the data below in Table 2.3.

Table 2.3 Average Values Estimated from Data

	K(1)	L(1)	M(1)	K(0)	l(0)	M(0)
Red - green	1.198786	1.324752	0.653244	-0.197	-0.10202	-0.15015
Green - blue	-9.40881	1.826829	1.06142	-1.16904	-0.15412	-0.11813
Blue - yellow	-3.16437	0.059393	1.049465	-1.03563	-0.14758	-0.10907
Yellow - red	2.372236	-2.51783	24.09047	-0.66844	-0.75958	-0.05208
red - blue	0.97031	1.09209	1.077728	-0.12416	-0.11839	-0.12256
green yellow	0.542132	0.514793	1.156846	-0.0272	0.001425	-0.09531
red - yellow	0.05367	0.996289	1.498581	0.249841	-0.13263	-0.20166

2.4.3 Distance residual

A third model can be developed when we look closer at visual impact of these particles on the contrast between the background and the foreground. The foreground object is closer to the viewer and has less fog or blowing snow in front of it than the background. Also, the distance can have an impact on the color impinging on the eye.

In the measurements that we made, the background was a neutral grey object placed farther from the viewer than the foreground color objects. The third model can be broken into equations as follows:

Background color

12) $Rb(s) = kb(1)*Rb(o) + kb(0)$

13) $Gb(s) = lb(1)*Gb(o) + lb(0)$

14) $Bb(s) = mb(1)*Bb(o) + mb(0)$

Foreground color

15) $Rf(s) = kf(1)*Rf(o) + kf(0)$

16) $Gf(s) = lf(1)*Gf(o) + lf(0)$

17) $Bf(s) = mf(1)*Bf(o) + mf(0)$

If we assume that the coefficient values are constant for measurements given at a single time and reflect the impact of the intensity of the snow and fog, we need four independent measurements to determine them. The other background color measured at a similar distance was the dark green of some evergreen trees. This measurement may be problematic because under heavily overcast snowy conditions the trees become almost black. Since nothing can be blacker than the blackest black in the environment, the inclusion of this measurement in these calculations may introduce a saturation non-linearity rendering a null result.

We cannot do a similar analysis as in the previous sections because there is a lack of non-saturated background data. If we examined the data as if the background and foreground were at the same distance we would end up with the result of model 2.

2.4.4 Summary and Results

Our goal was to try to determine the color that snowplows should be painted to lessen or eliminate the possibility of creating an equiluminant situation when the vehicle is in fog or blowing snow. To do this, we needed to extract a model of what snow or fog do to the perceived luminance and chromatic channel energies. We measured patches of color using a spectrophotometer under a variety of weather conditions. During the analysis of this data we created three models – each successive model increases the complexity of the analysis while at the same time moves us closer to the physical reality.

The measured data did not support any of the models well. In fact, we are pretty sure that the first two models we presented were too limited to capture the essence of what was truly happening. The third model, we believe, is capable of capturing the complexity of the real situation but needs different kinds of measurements and controls over the measurements to draw any fine conclusions.

We can roughly look at our results using all of these methods. We can glean from the data that colors which incorporate a predominance of red (i.e. yellow, red, magenta, orange) seem to be pushed into an equiluminant situation more easily than others. This does not conflict with our results from previous work.

We cannot, presently, from this data determine how bad this situation is or to what extent other colors might provide better performance. We cannot with much confidence tell you, for example, whether blue is better than green. These measurements and the analysis supported by this part of the grant have given us the knowledge of how the measurements need to be improved to give us a handle on this question. These improvements are outlined in our conclusion.

CHAPTER 3
Research on Perception

3.1 Introduction
Luminance Contrast and the Ability to Perceive Motion

Recent research indicates low luminance contrast lowers the perception of velocity so that motion appears to be slower than it really is. Snowden (5,6) and his colleagues placed subjects in a driving simulator and asked them to travel at a specific speed under both fog and clear conditions. They found that on average people drove 10 miles per hour faster in simulated fog than in the clear condition. Mr. Ed Fleege, formerly of Mn/DOT, measured vehicle speed versus fog density on Thompson Hill outside of Duluth, MN in 1995 [7]. That study showed that there was a general trend for drivers to slow their speed with fog intensity but not nearly enough. With clear visibility (greater than 1000 meters), people averaged 112 km/hr. The drivers did slow down in fog but only to 100 km/hr. Hawkins [8] demonstrated that motorists slow down as fog intensity increases on a high traffic density roadway, but they do not slow sufficiently in light of the conditions. Mr. Fleege has pointed out the surprisingly high number of rear-end collisions with snowplows occur during daytime rather than night when contrast would be higher. Snowplows work in conditions of poor visibility and create low luminance contrast conditions for drivers that follow the snowplow. Blowing snow and fog may create a near equiluminant situation in which the moving object is almost equal in luminance to its background. This means that motion information is carried primarily by color contrast. When this occurs, objects appear to slow down. This means that if blowing snow creates a close to equiluminant situation, drivers would be able to detect the back end of a snowplow but not be able to perceive that they are approaching it. When they do detect approach, the pattern of motion would appear to be much slower than it actually is.

Why is motion so important to the perception of impending collision?
It is symmetrical expansion of the image on an object in a viewer's retina that specifies the approach of that object and provides information for impending collision (9). It is the constant size of the image that indicates that one is traveling the same speed as the object ahead. Optical flow field information is all-important for the control of locomotion. It literally tells the viewer where he or she is headed and whether there is clear space ahead or an obstacle. Other depth cues such as binocular disparity and the vergence angle between they eyes provide very little information for a reduction in the distance between a driver and the vehicle ahead because of the long distances at which driving decisions must me made on the road and the fact that binocular depth sensitivity drops off rapidly with distance. The differences in the images presented to our eyes is limited by the fact that human eyes are only about 9 cm apart. As a result, beyond 3 meters we receive little useful information other than motion that could help a driver perceive that a collision is imminent.

On the other hand, skilled drivers are exquisitely sensitive to optical expansion information for approach under high contrast conditions. This is demonstrated by the fact that crashes are generally rare on highways with a very high density of traffic traveling at very high speeds. Drivers constantly adjust their speed over long periods of time to match the speed of the car ahead by controlling the pressure on the gas pedal. When a vehicle that is ahead slows, the driver that follows behind detects the optical expansion of the car ahead. The driver lifts up on the pedal to slow his or her car and keep constant size rather than being allowed to expand or contract.

During bright daytime conditions the luminance contrast between the snowplow and its surroundings can be powerfully reduced. Low luminance contrast, we believe, reduces the ability of drivers to detect that they are approaching the snowplow ahead and will crash into it unless they slow down. Impaired ability to detect the motion pattern that specifies approach will delay the detection of approach and give the driver of the following vehicle less time to respond. If this is the case, low luminance contrast will interact with all of the other causes of snowplow crashes listed above and greatly increase the probability of a crash.

3.2 Experimental Study 1: The effect of luminance contrast on the threshold for discrimination of approach from withdrawal.

3.2.1
Introduction

The purpose of this experiment was to test the hypothesis that low luminance contrast (the difference in brightness between a vehicle and its background) reduces the ability of drivers to discriminate approach from withdrawal. The approach was to simulate the approach and withdrawal of a vehicle on a computer screen. Approach was simulated by the expansion of a square on the screen while for withdrawal the square contracted. The velocity with which the sides of the square moved apart or together was varied to create a situation in which the viewer could see the simulated vehicle but not detect that it was being approached.

Approach and withdrawal occurred with equal frequency in a random order to measure the lowest velocity or threshold at which the participant could discriminate these events. The computer program measured whether the participant was correct or made an error on each trial and adjusted the velocity accordingly over trials. If the participant was correct on several trials the velocity was lowered until an error was made. That is, the velocity was slowed to a point that the participant could no longer discriminate approach from withdrawal. When participants made errors the velocity was increased until correct responses occurred. In this way the velocity was increased and decreased so that over 75 trials the computer program found the velocity at which the observer was correct in 80% of the trials. By carrying out this procedure many times, a stable and highly reliable estimate of the threshold is obtained. Although research on motion processing has found that lowering luminance contrast slowed the perceived velocity of moving contours, there were no studies in the literature that explored whether lowering luminance contrast raised the threshold for the detection of optical expansion and made it more difficult to perceive approach and impending collision. Because fog and the snow cloud created by a snowplow lower luminance contrast, this study was carried out to see whether these conditions would increase the velocity threshold. The rate of expansion of the image of a vehicle increases as a driver approaches from the rear. If the threshold were increased the driver would first be able to detect approach at a closer distance.

By collecting a great deal of data from a small number of highly practiced participants, who are strongly motivated to perform at the highest level, researchers in the field of psychophysics over a century, have been successful at measuring the limits of the functioning of sensory and perceptual systems. By measuring the threshold, the effects of differences in motivation and other cognitive factors are minimized and highly reliable measurements can be made. One goal of this work was to explore whether well-understood traditional psychophysical methods could be made useful in investigating the real world problem of how to reduce crashes with snowplows.

3.2.2 Research Method

Participants: Four 20 to 22 year old undergraduates at the University of Minnesota served as observers. They were compensated for participating in the study.

Apparatus: A Linux operating system based computer program generated a display on an Hewlett- Packard computer and displayed it on a screen of a computer monitor that was 33cm wide and 22cm high. The display consisted of a square that expanded or contracted on the screen to simulate a vehicle that either approached the viewer or withdrew. The participant's eyes were 353cm from the screen. They were seated at a table to which a chin rest was attached. A computer keyboard was placed on the table and the participant responded by pressing one of the two arrow keys. The arrow pointing toward the participant was used to indicate the judgment of approach while the arrow pointing away from the participant indicated withdrawal. The chin rest was positioned 102cm from the floor and was at the same height as the center of the computer display. A large sheet of foam core board was position 232cm from the chin rest and occluded the region surrounding the monitor. The board was positioned 121cm from the surface of the monitor screen. A 14.6cm inch wide by 13.3cm high aperture in the center of the board made it possible for the participant to see only the computer screen. The aperture was used to enhance the experience of depth change as the display expanded and contracted. Overhead fluorescent lights provided the ambient light in the experimental room.

The Displays: The surround on which the simulated snowplow was presented was set to black and would have been 0 cd/m^2 (candelas per meter squared) if the experimental room were totally dark. In this study the fluorescent lights were on, creating a moderate level of illumination. Because of the ambient light reflecting off the surface of the computer monitor the effective luminance of the background was 9.0 cd/m^2. In the low contrast condition the square that simulated the snowplow had a luminance of 12.0 cd/m^2. This difference is luminance, a 75% increase over the background, was well above the threshold for detection. In the high contrast condition the luminance of the square was 102 cd/m^2. This presented a ten-fold increase in luminance over the background.

At the beginning of each trial the square was presented in the middle of the screen. The initial size of the square was varied randomly over trials and was one of four sizes, 9.0 cm, 9.3cm, 9.6cm, 9.9cm, or 10.2cm on a side. The square appeared on the screen for a 1 second period approximately 3 seconds after the previous response. The animated displays were presented at a frame rate of 30 frames per second. The program used to generate the animated expansion and contraction displays produce motions that could be both very rapid and very slow without flicker.

In addition to expansion and contraction the image of the simulated snowplow remained in the middle of the screen or translated in one of 8 directions on each trial at 9mm/second. The direction of this motion was selected at random and was either a vector of 0, 45, 90, 135, 180, 225, 275, or 315 degrees. This translational motion is similar to the changes in the position of a vehicle that is being followed as it turns around slow curves or goes up and down hills. In addition to making the display more realistic the translational motion was essential for the success of the experimental paradigm. It is important that the participants attend to the expansion and contraction of the whole form. We found in pilot testing that if the image does not translate across the screen the participants adopt a strategy of attending to only one edge of the image and make their decision of whether the display approached or withdrew based on whether a single contour moved to the left or the right. By making the display translate we forced the participants to attend to the overall display and respond to approach and withdrawal rather than motion at a particular location on the screen.

Procedure: Observers sat on a comfortable chair and positioned their head so that it rested on the chin rest. They were instructed to watch the screen through the aperture and decide whether the square object appeared to approach or withdraw from them. They were told that approach trials would occur in a random order and approach and withdrawal trials would occur with equal frequency. When the display was judged to be an approach trial, the arrow on the keyboard pointed toward the observer was pressed. On withdrawal trials the arrow pointing away from the observer was pressed. Two sounds indicated whether the choice was correct or an error. The QUEST(10) procedure adjusted the velocity of the display from trial to trial to measure the threshold defined as the velocity at which the observer was correct on 80% of the trials. This highly efficient method of measuring threshold is an adaptive psychometric procedure that places each trial at the current most probable Bayesian estimate of threshold.

Experimental Design: There were two conditions in the study, high contrast presentation and low contrast presentation. Participants made 75 judgments in each condition in each session to obtain a measure of the thresholds. The order of testing in the conditions was randomized. Five or more sessions in each condition were run first as practice over a period of one week. The data for the study consisted of the thresholds on at least 11 subsequent sessions in each of the two conditions. The observers collected the results over a period of two weeks.

3.2.3 Results

The observers were able to detect the presentation of the square on each trial in both the low and high contrast conditions. We conducted a paired-sample t-test to examine the effects of contrast on the threshold for discrimination of approach from withdrawal. The result for each of the four subjects indicated that there was a statistical significant difference between the two conditions. Following is the paired 2-tailed t-test results of each subjects: Subject H, $t(12) = 9.29$, $p < .001$, Subject G, $t(10) = 2.24$, $p < .05$, Subject J, $t(11) = 7.44$, $p < .001$, and Subject T, $t(11) = 5.53$, $p < .001$. The average threshold and standard deviation for each observer is presented in Table 3.1. An analysis of variance (ANOVA) with the contrast factor (High vs. Low) and the subject factor revealed that there was a significant interaction between contrast and subject. $F(3, 88) = 6.37$, $p < .01$. For three of the subjects there was a 3 fold or more increase in threshold when contrast was lowered. This increase was significantly less for subject G, although it was still substantial.

There were also two main effects: Contrast, $F(1, 88) = 110.49$, $p < .001$, Subject, $F(3, 88) = 10.34$, $p < .001$.

Table 3.1. Velocity thresholds for Low Contrast and High Contrast conditions for 4 observers and the thresholds averaged over participants.

		Subject H	Subject G	Subject J	Subject T	Combined Data
Low Contrast	Mean	0.47	0.26	0.55	0.62	0.48
	SD	0.11	0.12	0.17	0.26	0.17
High Contrast	Mean	0.17	0.18	0.21	0.21	0.19
	SD	0.05	0.07	0.07	0.07	0.07

Note: The velocity scale values have equal interval and ratio properties and are presented in arbitrary units. Zero on this scale indicates the absence of motion. Higher values indicate that a higher velocity was required to obtain correct responses on 80% of the trials. SD indicates standard the deviation around the mean.

3.2.4 Discussion

This study found clear evidence that luminance contrast has a marked effect on the ability to detect that one is closing on a simulated vehicle. The average velocity needed to discriminate approach from withdrawal increased from .19 velocity units to .48 when contrast was reduced. This average 2.5 fold increase in threshold means that instead of detecting approach at distance, for example, of 300 meters at high contrast, one would have to approach to only 120 meters to first be able to detect approach. That is, only at 120 meters or closer would the retinal velocity be above threshold.

Because snowplows create a snow cloud that reduces the luminance contrast presented to a following vehicle, the lighting on the rear end of snowplows should present a high level of luminance contrast. This could be arranged by increasing the size and brightness of the lights. Placing the lights as far from the center of the vehicle as possible would maximize the retinal velocity of the lights and improve the driver's ability to detect approach. For expansion rather than translation to be perceived at least two lights on the opposite sides of the snowplow must be visible. If only a single light or light bar above the snowplow were visible it would create less retinal expansion than bars at the left and right sides of the snowplow. In addition, the cover for the lights and the air stream around them should be designed to insure that snow would not stick to them and make them invisible.

3.3 Experimental Study 2: The effect of luminance contrast on the threshold for discrimination of approach from withdrawal under simulated daylight conditions.

3.3.1 Introduction

The purpose of this experiment was to examine whether low luminance contrast would raise the threshold for the discrimination of approach from withdrawal using a display in which the background was light and the simulated snowplow was darker than the background. The goal was to investigate whether we could replicate findings of Experiment 1 under conditions that simulated driving behind a snowplow that generates a snow cloud on a bright day.

3.3.2 Research Method

Subjects: Three of the same participants who served in the previous study participated in this experiment. All had extensive practice at the task before the data collection began.

The apparatus and procedure was the same as in the previous study.

Displays: Both conditions presented low contrast displays. In the Daylight condition the displays had a background luminance of 102 cd/m2 and the square had a luminance of 92 cd/m2. These values were selected to make it easy to detect the square against the background. In the Night Condition the luminance of the background was 9.0 cd/m^2 and the square that simulated the snowplow had a luminance of 12.0 cd/m^2.

3.3.3 Results

In order to test the effect of daylight on the threshold for discrimination, two conditions were compared in a paired-sample t-test. The Daylight condition presented a darker block against a lighter background, simulating daylight conditions, and the Night condition the square was lighter than a dark background. The displays in both conditions were presented for 1000 ms (milliseconds). Each of the three participants showed very similar performance in the two conditions (see Table 3.2). For all subjects there was no significant difference between the two conditions: Subject H, $t(10) = 1.30$, $p > .05$ Subject G, $t(10) = 1.11$, $p > .05$, Subject J, $t(11) = 1.12$, $p > .05$.

Table 3.2. Velocity thresholds for Night and Daylight conditions for 4 observers and the thresholds averaged over the observers.

		Subject H	Subject G	Subject J	Combined Data
Low Contrast in Night	Mean	0.47	0.26	0.55	0.42
	SD	0.11	0.12	0.17	0.13
Low Contrast in Daylight	Mean	0.58	0.32	0.56	0.49
	SD	0.14	0.10	0.27	0.17

Note: The velocity scale values have equal interval and ratio properties and are presented in arbitrary units. Zero on this scale indicates the absence of motion. Higher values indicate that a higher velocity was required to obtain correct responses on 80% of the trials.

3.3.4 Discussion

This study found that low luminance contrast produces the same high threshold for the detection of approach whether the background is dark and the simulated snowplow is lighter or the reverse. This finding supports the generality of the conclusion of Experiment 1 and rules out the possibility that the high threshold that was observed was due to the specific luminance values that were presented in the displays of the first experiment.

3.4 Experiment 3: The effect of discontinuous presentation on the threshold for discrimination of approach from withdrawal.

3.4.1 Introduction

Bright flashing and sometimes moving lights are a pervasive feature of snowplows. Such lighting does an excellent job of alerting drivers to the fact that there is some sort of emergency vehicle ahead. The transient nature of the flashing increases apparent brightness beyond that produced by the very high luminance of the lights themselves. It is clear that the visual system is very sensitive to transient signals and such signals do attract attention.

The purpose of this experiment was to investigate the effects of having the image of the simulated snowplow flash on and off over the 1 second display period at the rate of 3 flashes a second and 5 flashes a second and to compare performance in these conditions with a no flash condition. Flash patterns were similar to two widely used patterns on snowplows that are sold by the Whelen Company (http://www.whelen.com/). In addition, the contrast between the square and background was varied to produce high and low luminance contrast versions of each of the three timing conditions.

The hypothesis explored in this study was that as the number of flashes increases, sensitivity to motion would decrease. Continuous motion over time is the normal input required for the perception of velocity and the more discontinuous the stimulation the poorer the input to the visual system. Croft (1971) has found that stroboscopic presentation impairs the ability to perceive motion. Of course, when stroboscopic displays are presented at more than 20 frames a second, flicker cannot be detected by most viewers and motion perception is not impaired. The fact that motion is not available when the display is off and not visible could also account for reduced performance when a display is flashed on and off (the duration of motion is reduced). Although, the amount of time the moving display is available to the participant is reduced in the two flash conditions from 1000 meters/second (ms) to 500 ms, the time the motion is presented in the 3 and 5 flash conditions is equal. If performance were poorer in the 5-flash condition than in the 3-flash condition, it would suggest that the number of flashes by itself reduces performance. This study did not attempt to study the effects of the very bright flashing lights used to make snowplows more conspicuous. These lights may have an even more powerful harmful effect on the ability of drivers to detect approach because the glare they create may make it difficult to sense expansion information for approach.

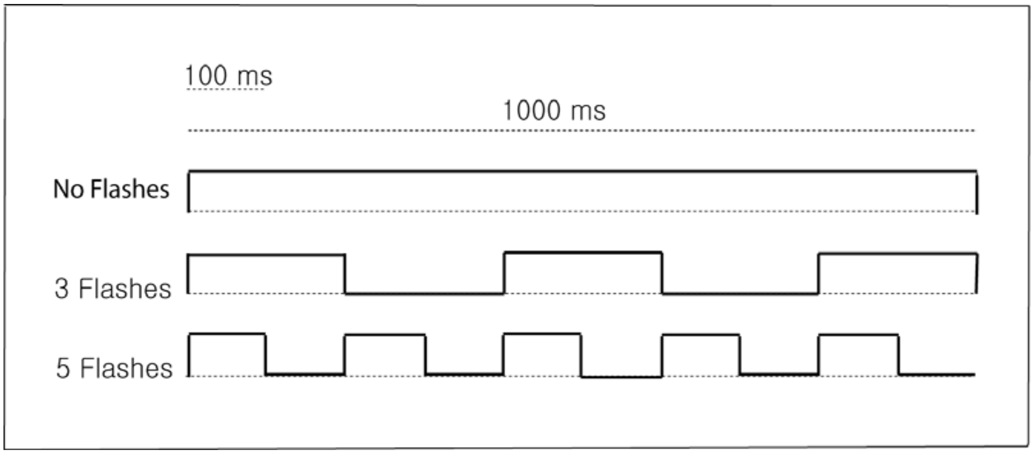
3.4.2 Experimental Method

Participants: The 4 participants who served in Experiment 1 took part in this experiment. All had extensive practice at the task before the data collection began.

Apparatus and Procedure: The apparatus and procedure was the same as in the previous study. The high and low luminance levels used were the same as in Experiment 1.

Experimental Design: There were 6 conditions in this study. In three of the conditions a high contrast display was used and in the other three conditions low contrast displays were used. Participants were tested on a No-Flash condition in which the square was presented continuously for 1000ms, on a 3-Flash condition in which the display was visible and invisible for successive 200ms periods and on a 5-Flash condition in which the square was visible and invisible for successive 100ms periods. The three timing patterns are presented in Figure 3.1. Participants made 75 judgments in each condition in each session to obtain a measure of the thresholds. The order to testing in the conditions was counterbalanced using a Latin-square method. The data for the study consisted of the thresholds on each of the 6 conditions collected at 12 or more subsequent sessions. The observers collected the results over a period of 6 weeks.

Figure 3.1. Depiction of timing pattern of square.



Note: In the No Flashes condition the square was presented continuously for 1000ms. In the 3 Flashes condition the display was visible and invisible for successive 200ms periods. In the 5 Flashes condition the square was visible and invisible for successive 100ms period. In both the 3 and 5 Flashes condition the display was visible for 500ms.

3.4.3 Results

The average thresholds for the 4 participants combined are presented in Figure 3.2. The thresholds for each of the participants are presented in Figure 3.3.

Figure 3.2. Averaged velocity thresholds for Low Contrast and High Contrast conditions.

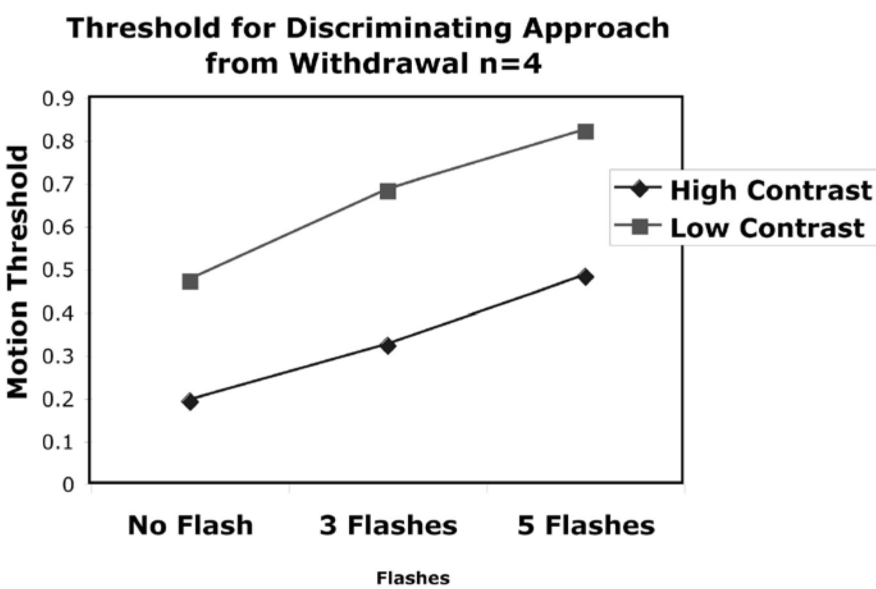
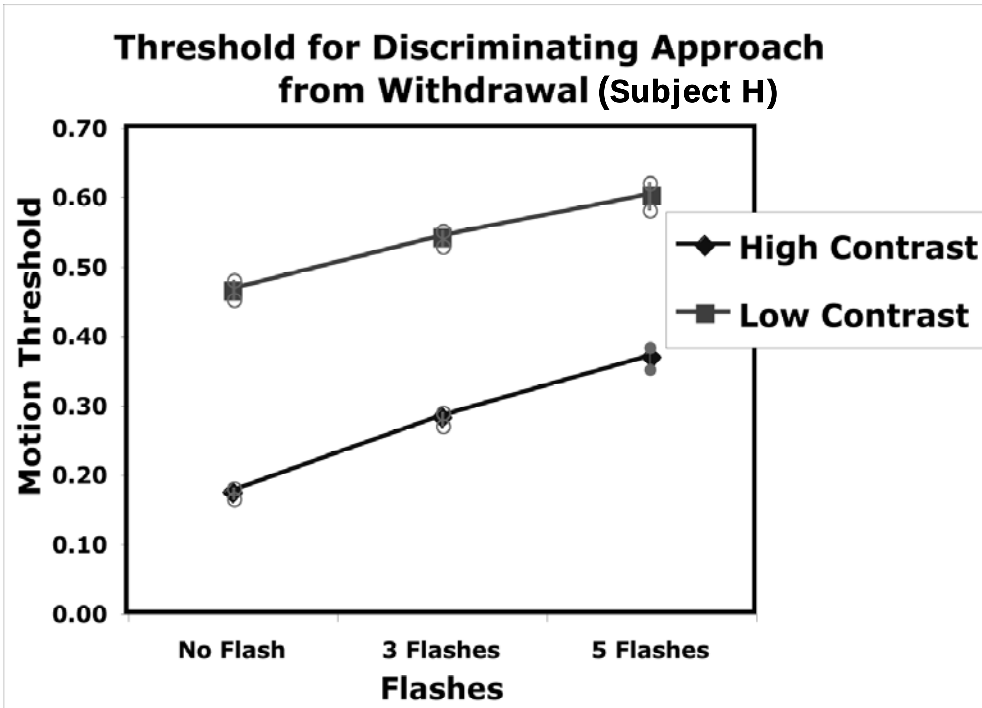


Figure 3.3. Velocity thresholds for Low Contrast and High Contrast conditions.



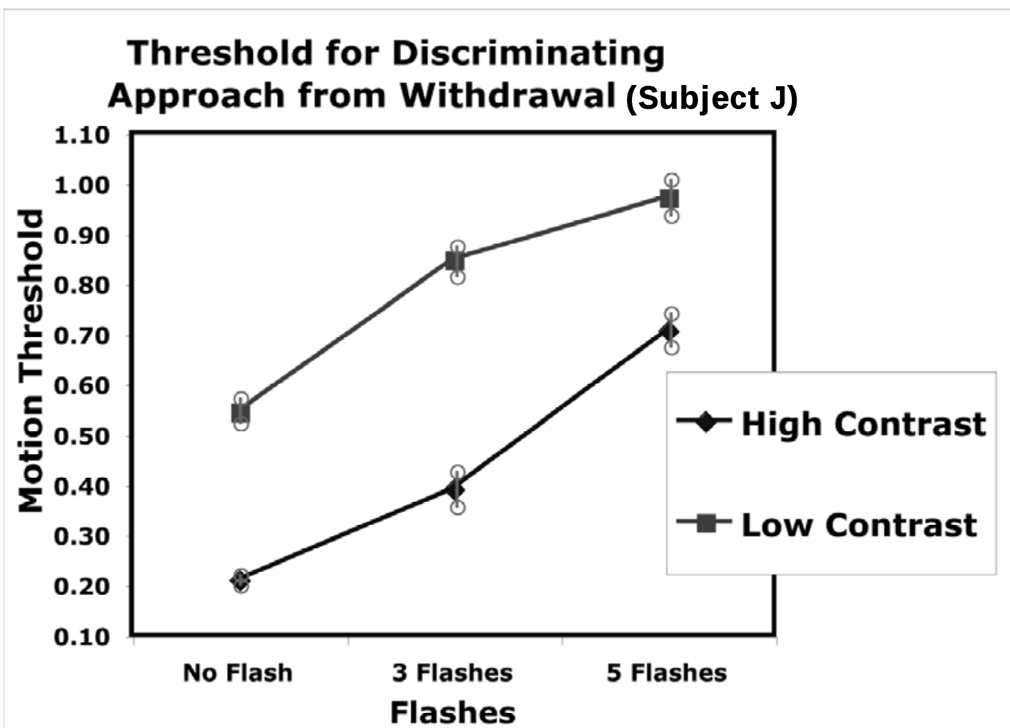
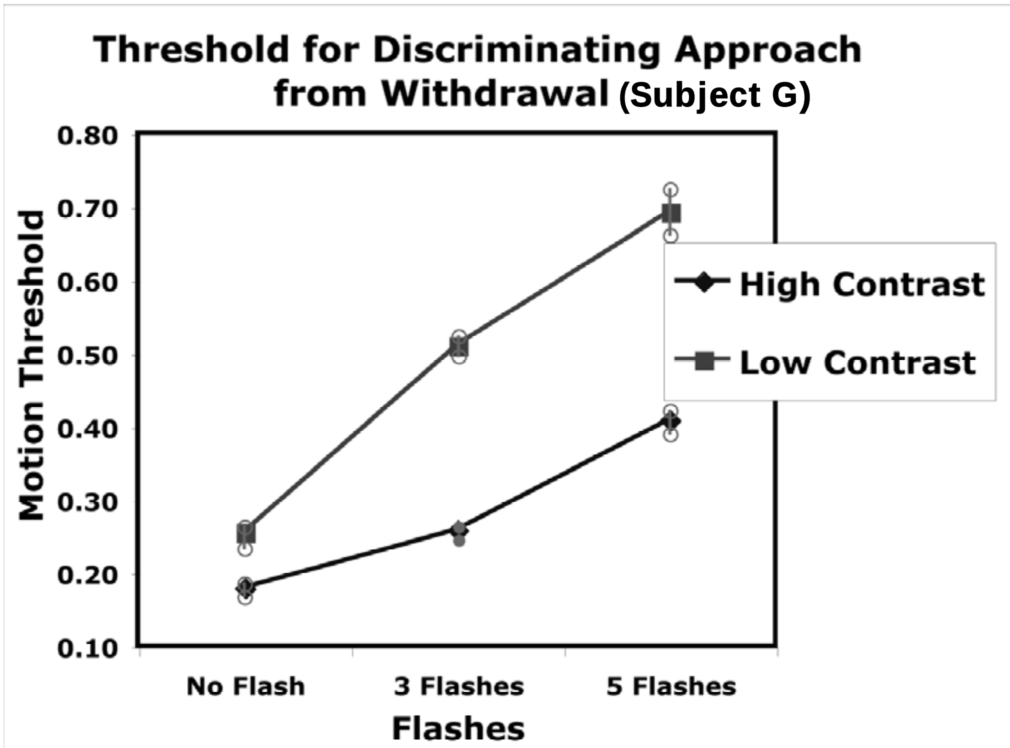
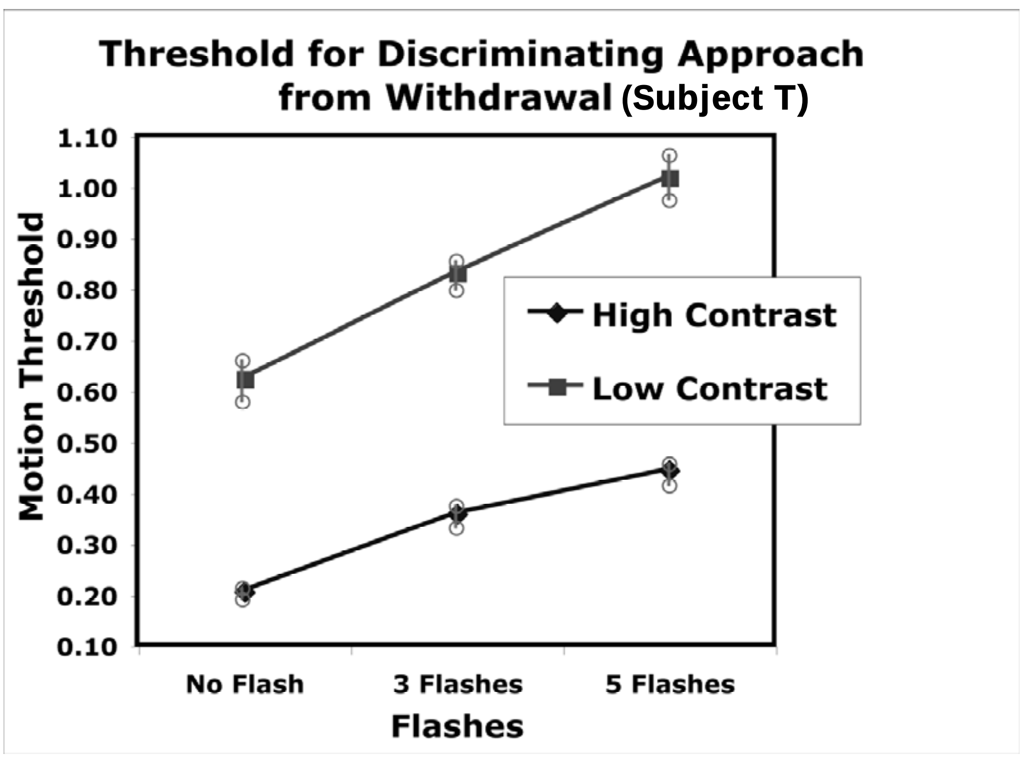


Figure 3.3 (continued) Velocity thresholds for Low Contrast and High Contrast conditions





Note: Letters, (H) etc., indicate individual participants. Vertical bars indicate standard error values.

An analysis of an analysis of variance (ANOVA) with 3 (No-Flash vs. 3-Flashes vs. 5-Flashes) × 2 (High vs. Low Contrast) × 4 (Subject) revealed that there were significant main effects for all 3 variables: Flashes, $F\ (2, 268) = 91.92$, $p < .001$, Contrast, $F\ (1, 268) = 285.09$, $p < .001$, and Subject, $F\ (3, 268) = 38.67$, $p < .001$. Post hoc tests that examined whether the differences between the pairs of conditions were significant were carried out using the Tukey method (11). The tests revealed that there were statistically significant differences between each pair: No Flash – 3 Flashes, $t(193) = 7.15$, $p < .001$ 3 Flashes – 5 Flashes, $t(193) = 6.33$, $p < .001$, No Flash – 5Flashes, $t(192) = 13.45$, $p < .001$. There were significant interactions between subject and contrast, $F(3, 268) = 11.472$, $p < .001$, and between subject and flashes, $F(6, 268) = 3.482$, $p < .01$. There was, however, no significant interaction between the number of flashes and the effect of contrast, $F\ (2, 268) = 1.301$, $p > .05$.

3.4.4 Discussion

As in Experiment 1 low luminance contrast more than doubled the threshold for the discrimination of approach form withdrawal. Drivers who could detect that they were approaching a snowplow or other vehicles at a distance of, for example, 300 meters under high contrast viewing conditions would have to approach to closer than 150 meters to detect approach. A driver that was beyond 150 meters would perceive that there is a snowplow ahead but could not detect that he or she was approaching it. The effect of flashing the displays on and off also raises the threshold for the perception of a potential collision. Not only was the threshold in the 3-flash condition higher than the No-flash condition but, in addition, the 5-Flash condition produces an ever higher threshold. It appears that as the number of flashes increases it becomes more difficult to detect approach. The effect of contrast and flashing appears to be additive. When performance in the best and poorest conditions is compared there is a more than a quadruple increase in threshold. This result strongly supports the hypothesis that flashing warning lights impairs the ability of a driver to perceive that he or she is closing on a vehicle. The faster the strobe rate, the greater the impairment. Steady burning lights provide drivers with the best information that they are approaching a vehicle that is ahead.

CHAPTER 4
Conclusions and Recommendations

4.1 Color Research

The goal of the research on color was to try to determine how snowplows should be painted to lessen or eliminate the possibility of creating an equiluminant situation when the vehicle is in fog or blowing snow. Different patches of a painted color surface were measured with a spectraphotometer under a variety of weather conditions. The color measurements were analyzed for the likelihood that they would create equiluminant conditions in blowing snow or fog. These same measurements were used to try to create a model of the impact of blowing snow and fog on perceived chromatic and achromatic contrasts. The model could then be used to predict an optimum color.

The direct analysis of the color patches roughly suggested that blowing snow and fog impacted colors that had red, orange, and yellow components most negatively. Three mathematical models were created to try to refine and expand this result. The first two of the models created were not able to sufficiently describe the measured results. The third model needed a different set of data to be measured before it could be assessed. This third model does show promise, both from a data collection and from a physical sense.

The color measurements and analysis were a much more complex task than originally imagined. As a result we cannot with much confidence recommend, for example, that blue is better than green. The measurements and the analysis described in this section do strongly suggest that it is essential to move this work closer to the real world driving conditions.

4.2 Perception Research

It is clear that while color differences between a snowplow and its background enhance the ability of the visual system to detect the presence of the snowplow, it is luminance contrast that makes it possible to perceive the expansion of image of the snowplow that tells the driver that collision will occur if he or she does not slow down. Unfortunately, when research is carried out to evaluate the effectiveness of rear lighting, viewers are normally asked to report under which lighting arrangement a snowplow is most easily detected. The answer to that question is different from the answer to the question of which type of lighting is best for perceiving approach. The effectiveness of lighting should be explored using a task that measures the ability to perceive approach.

The perception studies investigated the ability of the visual system to detect the expansion pattern that drivers use to know that they are approaching a vehicle that is ahead. The research found that low luminance contrast created by a snow cloud greatly reduces the ability to pick up that information. Effort is needed to enhance the luminance contrast of lighting on the rear of snowplows. In addition, flashing lights that increase the conspicuity of a snowplow substantially decreases the chances that a driver will perceive that a crash is imminent in time to respond. If only one kind of lighting were used, steady burning lights would be better than flashing lights. On the other hand, both the goals of making a snowplow conspicuous and of improving the ability of drivers to perceive approach could be maximized if both kinds of lighting were used. To minimize the negative effects, flashing lights should be placed so that they do not interfere with the visibility of steady burning lights. For example, flashing lights could be placed above the center of the snowplow and steady burning light bars could be positioned on its sides.

An analysis of the information that specifies approach suggests that steady burning lights should be placed as far from the center of the rear of the snowplow as possible. This will maximize the velocity of optical motion that will be presented to the following driver as that driver begins to approach to the snowplow. Higher velocity motion will generate optical expansion that can be detected at greater distances from the snowplow. Because the information for approach is optical expansion, lighting should be placed on opposite sides of the rear of snowplow so that expansion information for approach rather than translation in one directed is presented to the driver that is following the snowplow. A single light above a snowplow, which rises in a driver's field of view, may be perceived as a situation in which the snowplow is going up a hill or moving away while in fact the driver may be approaching the snowplow be moments away from a crash.

Finally, efforts are needed to insure that this lighting is does not become covered with a layer of snow and become invisible.

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