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Warning Light Flash Frequency as a Method for Visual Communication to Drivers

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Abstract

Service vehicles use flashing warning lights to indicate their presence to approaching drivers. Present standards offer ranges of flash frequencies to enhance conspicuity and avoid potential risks of photosensitive epilepsy or other issues. But, in practice, the flash frequency is not varied in specific situations. Previous studies have indicated that people interpret faster flash frequencies as more "urgent" than slower flash frequencies. Building on these findings, a laboratory study was conducted to identify whether drivers might be able to use cues from the frequency of flashing warning lights to anticipate how a service vehicle might behave in a work zone or other incident scene. The results suggest that even if they are not taught about the interpretation of different flash frequencies, drivers can differentiate between 1 Hz and 4 Hz flashing lights and learn to make accurate predictions about their meaning. The results also indicate that there are no reliable differences between 1 Hz and 4 Hz flashing in relation to a driver's ability to detect when a service vehicle has begun to move. Based on the results, a preliminary suggestion is made to use lights flashing at 1 Hz when a service vehicle is moving forward, and 4 Hz when it is traveling in reverse.

Construction, snow removal, towing, utility, and other service vehicles are required to include a lighting system that is designed to alert nearby drivers to where these vehicles are. These requirements are generally created using the Society of Automotive Engineers (SAE) guidelines that include what color the lights should be, their intensity level, and requirements for how they should operate (*1*, *2*). The introduction of new technologies such as light-emitting diode (LED) sources and computerized wireless controls has given these systems more options for how these lights can behave, and decreased power requirements for lighting (*3*).

Current standards and practices for warning lights could potentially be improved to increase nearby drivers' ability to recognize a situation that may improve service worker safety. For example, a new system could show an approaching driver if the service vehicle is moving toward or away from the driver with different flash frequencies. It has been argued that it would be possible to increase a service vehicle's recognizability through markings that would help other drivers to identify it as a truck and thus be more able to better determine whether it was moving or stationary. This, in turn, could reduce the number of accidents involving these vehicles (*4*). An objective of this study is to investigate how flashing lights might operate to help provide similar information to drivers.

Current guidelines specify that systems use flash frequencies that are between 1 Hz and 4 Hz, as these are rates that do not negatively impact drivers who suffer from photosensitive epilepsy (*5*). It has been shown that there is a difference in perceived urgency levels between 1 Hz and 4 Hz, with 4 Hz often being seen as more urgent (*6*, *7*). The ability to detect the relative motion of a service vehicle is also important. In a laboratory experiment (*8*), subjects showed that closure detection times (i.e., the times taken to notice that a preceding vehicle was starting to slow down) for lights with a minimum intensity that was 10% of their maximum intensity, were similar to closure detection times for steady-burning lights. Both were better than conventional flashing where the intensity goes from 100% to 0%, or on to off (*8*).

Combining new technologies with this knowledge could allow drivers to become more aware of these large service vehicles as they come closer to the driver, and of their relative speed and direction of movement. The present experiments were carried out to identify whether observers can reliably distinguish between 1 Hz and 4 Hz

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flashing in relation to the likely direction of motion of a scale model service vehicle, and to determine whether there are any perceptual differences between 1 Hz and 4 Hz flashing lights in relation to closure detection. An objective is to determine whether drivers can learn that a particular flash pattern means that the service vehicle is going to move in a particular direction, even if they are not instructed about this in advance. Such learning may allow them to anticipate how a service vehicle is going to move and thereby be able to respond more quickly and appropriately to it.

Experiment 1

Equipment

An apparatus was designed simulating a pair of vehicle-mounted warning beacons flashing simultaneously at different frequencies with a duty cycle of 50% and a peak luminous intensity scaled to mimic the appearance of lights with a luminous intensity of 600 cd, meeting SAE (*1*, *2*) requirements. The minimum intensity during the flash cycle was 10% of the peak intensity, consistent with the findings from Bullough and Rea (*8*). The pair of lights was suspended from an overhead track (Figure 1) and was designed to travel a distance equivalent to 300 m in scale (1:100). A simulated roadway surface was located under the simulated warning lights. The motion of the lights was provided by an electrical gear motor and belt. To provide position feedback to a computer, a potentiometer was also installed and was turned by the same belt that moves the suspended warning lights.

The simulated warning lights consisted of a pair of yellow LEDs that were mounted at a simulated height of 2.5 m, similar to the height used on a dump truck. A computer-controlled function generator provided the appropriate temporal information for a given condition to a specially designed constant-current power source which drove the LEDs with constant-current power. Pulse width modulation was not used to eliminate any likelihood of flicker detection by the study participants. The LEDs used had chromaticity coordinates (of 0.61, 0.39) in the International Commission on Illumination (CIE) 1931 (x, y) system, meeting SAE (*9*) requirements for yellow signal lights.

All of the equipment described above was controlled by a central computer running a specially written program in LabVIEW software. The program had the ability to control both the direction of travel and the speed of the suspended warning lights. It also had the ability to control the flash intensity and temporal characteristics. The aforementioned variables were all set according to a predetermined order read by the software from an input file. The software also used a computer keyboard to track the study participants' answers and reaction times, in addition to recording the position of the lights when the participants responded.

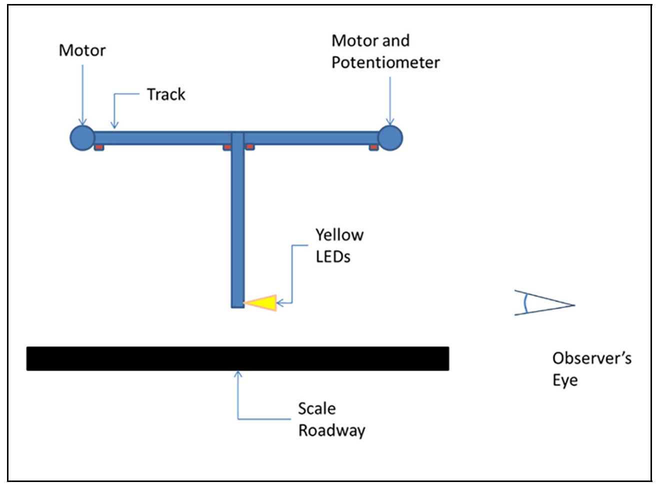


Figure 1. Side view of the experimental apparatus showing the track on which the yellow light-emitting diodes (LEDs) were suspended, the motors and potentiometer controlling the LEDs' motion, the scale model roadway, and the location of the observer's eyes.

Subjects and Procedure

The stimuli used in Study 1 had a flash frequency of 1 Hz or 4 Hz. The subjects were divided into two groups: one group in which 1 Hz represented a target that was moving toward the subject and 4 Hz represented a target that was moving away from the subject, and a second group in which 1 Hz represented a target that was moving away from the subject and 4 Hz represented a target that was moving toward the subject. Half the subjects were advised what the meaning of the flash rate was, whereas the other half was not, resulting in four subject groups. The lights always moved at a speed equivalent to 16 km/h regardless of direction or flash frequency.

Subjects of ages 18–30 years and over 50 years were recruited to participate. All participants were required to meet the minimum qualifications to hold a driver's license but were not required to have one. Further information on the subject groups is shown in Table 1.

Each participant sat approximately 1.5 m in front of the apparatus and was provided with a keyboard and a pair of noise cancelling headphones. Before starting the experimental session, the experimenter read a script to the subject providing general instructions. It was at this point that subjects in groups 3 and 4 were advised of the meaning of the flash rate. Next, the room lights were extinguished and the subject was allowed to adjust to the darkened ambient environment; nighttime conditions were simulated as a potential worst-case scenario

Table 1. Group and Participant Details

	Instructed	Toward	Away	# Subjects	Age	Sex
Group 1	No	1 Hz	4 Hz	8	2: 50+|6: 18–30	3 Female/5 Male
Group 2	No	4 Hz	1 Hz	9	2: 50+|7: 18–30	4 Female/5 Male
Group 3	Yes	1 Hz	4 Hz	9	2: 50+|7: 18–30	5 Female/4 Male
Group 4	Yes	4 Hz	1 Hz	7	2: 50+|5: 18–30	4 Female/3 Male

compared with daytime when other visual cues would be present.

After the adjustment period, the experimenter began the study. The simulated warning lights began flashing. The experimenter asked the subject to predict which direction the lights would be moving (toward or away) and recorded the answer in the LabVIEW program. Once the answer was recorded, the software waited a random amount of time between 3 and 5 s before beginning to move the lights.

Once the subject was sure that the lights had moved, they responded as quickly as possible by striking the "+" or the "Enter" key in the number pad on the right side of the keyboard. The "+" key was used to indicate that the lights were moving away from the subject and the "Enter" key indicated that they were moving toward the subject. The software recorded the answer and the distance the lights had traveled before detection of motion. Once the subject answered, the lights would turn off and move back to the starting point. If no motion was detected and the lights traveled the full distance, they turned off and were returned to their starting position in the center and the software recorded the missed trial. Each participant saw a total of 48 conditions.

Results

Figure 2*a* shows the accuracy of predictions of travel direction for each subject group as the study progressed (note that the data are presented in sets of 12 trials, each representing 25% of the total trials; this was done to assess whether performance changed over the course of the experimental session). The accuracy of groups 3 and 4 were generally higher than groups 1 and 2, which should be expected since they were told the meaning of flash frequency. Also, generally speaking, the accuracy of predictions improved over the course of the study, even for groups 1 and 2 who did not receive instructions about the nature of the different flash frequencies. In addition, the correct prediction percentages for groups 1 and 2 are above 50%, suggesting that they were able to learn what the flash frequency meant, although their prediction performance was never as high as that of groups 3 and 4 who received explicit instructions about the interpretation of flash frequency.

Figure 2*b* shows how accurately the study participants were able to detect the direction of travel. Again the results are presented in sets of 12 conditions. Regardless of whether the subjects received information about the meaning of the flash frequency, they were able to detect motion fairly accurately (all averages being above 75%). Groups that were instructed what the meaning of flash rate was, improved in accuracy over the course of the study, whereas groups that were not instructed did not show an obvious pattern.

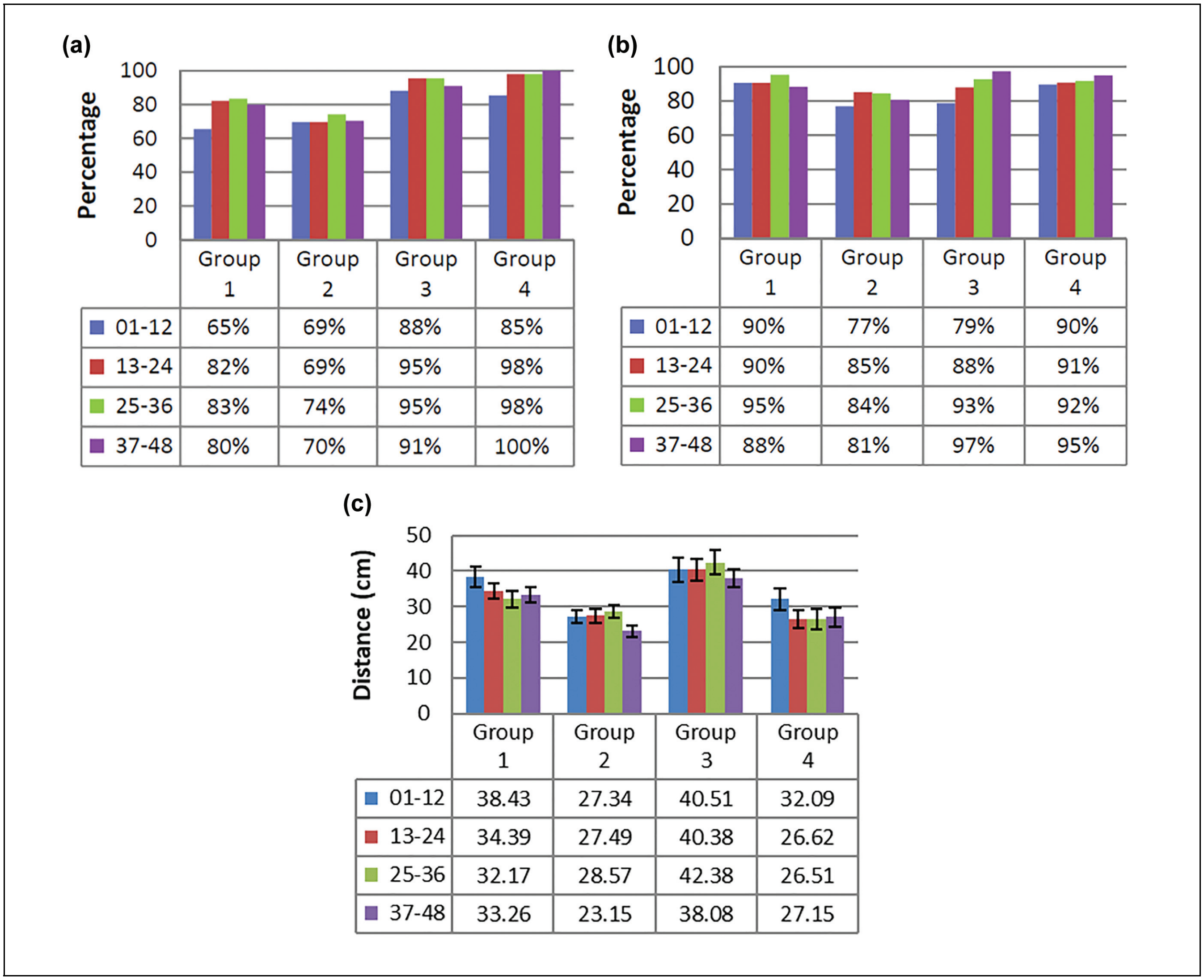
Figure 2*c* shows the average distance traveled at which the subjects responded that they detected motion (shorter distances indicate better performance). Results are again presented in sets of 12 conditions. A between-subjects analysis of variance (ANOVA, *Minitab 19*) was performed to test the effect of the order of trials (represented by each successive set of 12 trials) as well as the differences among groups and between participant age categories. There were statistically significant differences in distance among the groups ($F_{3,1552} = 27.4$, $p < 0.05$) and among the sets of 12 trials ($F_{3,1552} = 2.7$, $p < 0.05$), but not between the age categories ($F_{1,1552} = 0.8$, $p > 0.05$). None of the two- or three-way interactions among these factors were statistically significant. In all four groups, the average detection distance between the first and fourth sets of 12 trials improved (became shorter).

Figure 3 shows the performance of groups with similar style stimuli (i.e., groups 1 and 3 experienced 1 Hz toward/4 Hz away whereas groups 2 and 4 experienced 4 Hz toward/1 Hz away). On average, groups 2 and 4 performed better (earlier response) than groups 1 and 3. It was not clear whether the difference between these pairs of groups is related to the psychophysical stimuli or to differences in closure detection ability between the individuals allocated to these groups, so a follow-up experiment was conducted.

Experiment 2

Method

Study 2 was conducted in broadly the same way as Study 1, but with a few differences. Primarily, all of the subjects were naïve (i.e., none were instructed about the significance of flash rate). Additionally, the subjects were



(a)

	Group 1	Group 2	Group 3	Group 4
01-12	65%	69%	88%	85%
13-24	82%	69%	95%	98%
25-36	83%	74%	95%	98%
37-48	80%	70%	91%	100%

(b)

	Group 1	Group 2	Group 3	Group 4
01-12	90%	77%	79%	90%
13-24	90%	85%	88%	91%
25-36	95%	84%	93%	92%
37-48	88%	81%	97%	95%

(c)

	Group 1	Group 2	Group 3	Group 4
01-12	38.43	27.34	40.51	32.09
13-24	34.39	27.49	40.38	26.62
25-36	32.17	28.57	42.38	26.51
37-48	33.26	23.15	38.08	27.15

Figure 2. (*a*) Percentages of correct direction predictions in groups of 12 trials; (*b*) percentages of responses correctly identifying the direction of travel in groups of 12 trials; and (*c*) average detection distances (in cm) in groups of 12 trials. Vertical error bars in panel c show the standard errors of the mean.

not asked to predict the direction of the motion based on the flash pattern. Instead, they were asked to indicate the direction of travel, once motion was perceived, by using the keyboard in the same manner as in the previous study. The experimental results could help identify whether there were inherent advantages to any specific combinations of flash frequency and direction of travel.

After an answer was entered, or if no motion was detected and the lights traveled the full distance, the lights were turned off and were returned to their starting position in the center. After a random delay of between 3 and 5 s, the next condition began. Each participant saw a total of 48 conditions.

A total of eight subjects participated in this study, with an average age of 23 years and a range of 18–30 years, since no differences between age groups were previously found. The group consisted of two female and six male participants. As with the first study, all participants were required to meet the minimum qualifications to hold a driver's license but were not required to have one.

Results

Figure 4 shows the position at which subjects detected motion. The data is presented in groups of 12 (again representing 25% of the total trials) and is broken out by the direction in which the simulated warning lights were moving. Subjects seeing 4 Hz in the first 12 trials generally responded sooner than those seeing 1 Hz, regardless of travel direction. However, this difference tended to disappear as the study progressed.

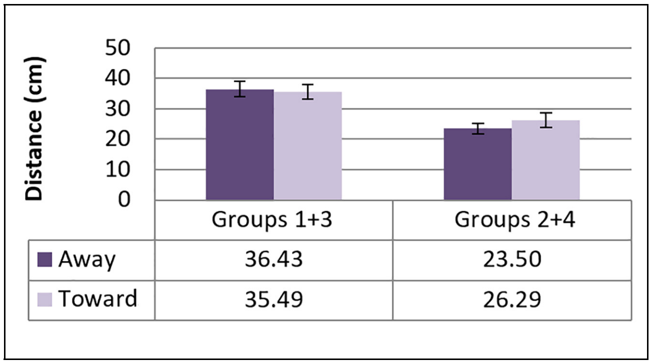


Figure 3. Average distances for the simulated warning lights when motion was detected by the subjects for trials 37–48. Vertical error bars show the standard errors of the mean.

It can be seen that, by the time the last set of 12 trials was performed, the differences in detection performance between the flash frequencies was relatively small, especially for the lights moving toward the observer (Figure 4*b*). This suggests that the performance difference between 4 Hz toward/1 Hz away and 1 Hz toward/4 Hz away was more likely to be because of individual differences in ability among the individuals assigned to those groups than to a psychophysically predictable factor associated with a particular combination of flash frequency and motion direction.

Discussion

The results of this laboratory study, taken together, suggest that flash frequency can be used as a reliable tool for communicating to drivers about the intended motion of a service vehicle. Even when subjects in the first experiment were not instructed about the relationship between frequency of flashing and the eventual direction of travel, they were able to make predictions about the direction of travel with greater than 60% accuracy, and their performance improved slightly throughout the experiment.

Based on the results of the second experiment, there do not seem to be any particular advantages or disadvantages to using either 1 Hz or 4 Hz flashing in relation to the ability of observers to detect motion once it has begun. Over time, initial performance was somewhat better for 4 Hz flashing, but that difference diminished after a few dozen trials. The greater urgency associated with 4 Hz flashing relative to 1 Hz (*6*, *7*) may have caused subjects to focus more attentively on those stimuli at the beginning of the experiment and, if so, perhaps this effect lessened over time.

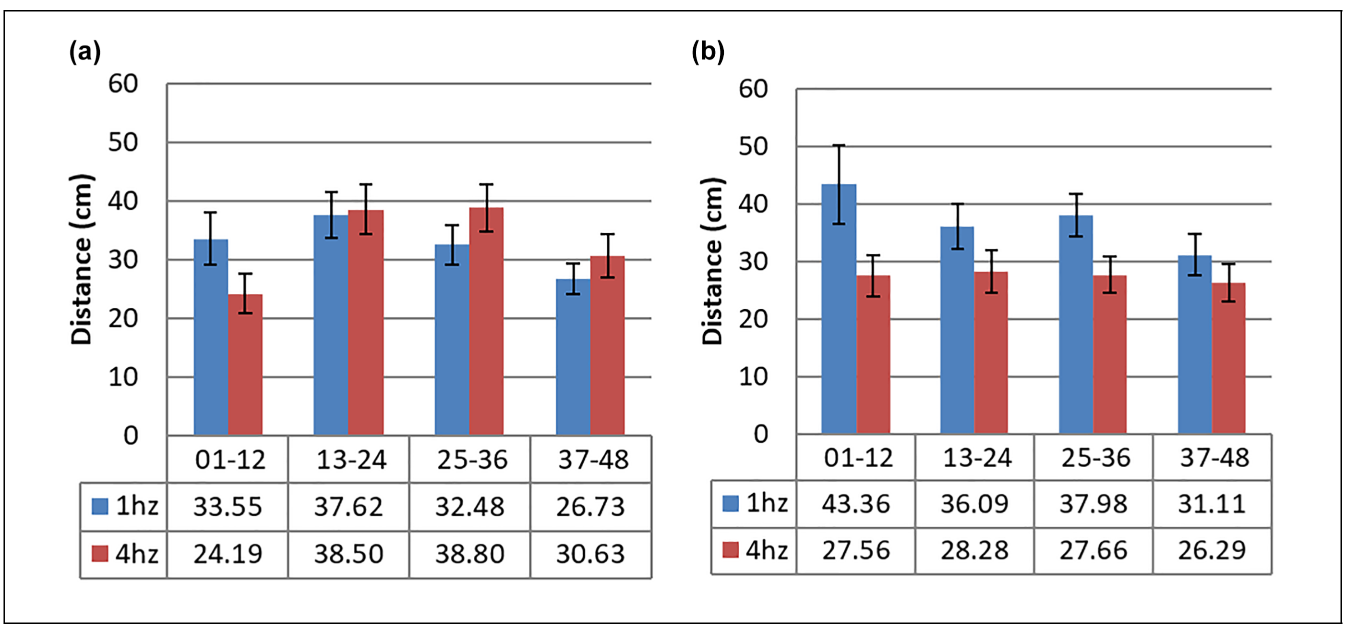


Figure 4. Average distances for the simulated warning lights when motion was detected by the subjects: (*a*) motion away from the subjects and (*b*) motion toward the subjects. Data are presented in groups of 12 trials. Vertical error bars show the standard errors of the mean.

Taken together, though, the results suggest that changing the frequency of flashing lights could be an effective cue for drivers broadly ranging in age to indicate operations that might be less safe or unusual. For example, a service vehicle's flashing lights could change from 1 Hz flashing to 4 Hz flashing when the vehicle was traveling in reverse. The higher urgency associated with faster flash rates would correspond appropriately to the service vehicle operator's likely reduced visibility when driving a truck in reverse. Importantly, even if drivers were not taught this correspondence between flash frequency and driving direction, the present results suggest that they could learn it over time.

Of course, the results of this laboratory study should be confirmed under full-scale, real-world conditions before they could be implemented into warning light practices for service vehicles, but these findings are promising for potentially helping to improve safety in work zones and other incident scenes where service vehicles and front-line service workers are present. In particular, the so-called moth-to-flame effect (*10*, *11*) has been demonstrated in some studies involving driving approaches toward flashing lights, where drivers steer toward the lights. Whether the flash patterns investigated in this preliminary study could interact with such an effect is not presently understood.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: J. Bullough and T. LaPlumm; apparatus development: N. Skinner; data collection: T. LaPlumm; data analysis: T. LaPlumm and J. Bullough; manuscript preparation: N. Skinner from a draft by T. LaPlumm. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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