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**TNO Memorandum TM-04-M062**

# Implementation and testing of the driving scenarios in the TNO driving simulator

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# Contents

# 1 Introduction

Advanced Medical Optics (AMO) have asked TNO Human Factors to conduct a driving simulator study in which the performance of intraocular lenses (IOLs) is measured. In the study it is tested whether there is a significant difference between driving with the Enhanced Monofocol IOL and the standard spherical monofocol IOL. The visual aspects of driving with the above described lenses will be established by measuring traffic sign detection and recognition distances, hazard detection, and driving behavior.

For this study TNO has modeled appropriate driving scenarios in our driving simulator. As requested by AMO, these scenarios consist of clear weather at night, fog at night and glare at night.
The task of the participants (wearing two different IOLs) will be detection and recognition of traffic signs and detecting and avoiding hazardous events (pedestrians and objects).

- The *detection* distance is defined as the distance at which an object is detected, without knowing the type of the object (sign, pedestrian, etc.). At this distance the object in the driving simulator is perceived as a vague blob at the horizon. In general these distances are rather large (up to 800 m).
- The *recognition* distance is defined as the distance at which a sign or objects used in the hazard events can be identified (e.g., warning sign with to the right, place name sign with “Aachen Ost”, pedestrian looking to the right).

This memorandum describes the implementation and testing of the driving scenarios. More specifically, it describes the imaging capabilities of the driving simulator in terms of the screen luminances and the contrasts of the signs and hazardous events. With this detailed description, the relationship between sign and hazard recognition in the simulator and in the real world is demonstrated.

This memorandum also describes the details of the experimental design in terms of the order of events and the balancing of conditions over the participants.

# 2 Driving scenarios

The driving simulator experiment consists of three different scenarios:
1. Clear weather at night
2. Fog at night
3. Glare at night

In this chapter, the exact imaging capabilities in terms of luminances of the driving simulator will be described.

## 2.1 Clear weather

All driving scenarios are modeled in a night scene. In order to get an idea of the luminance performance of the driving simulator at low light level we measured various luminances in the traffic scene, as a function of the so-called "time-of-day" variable (TOD), a parameter of the driving simulator. The TOD value can be varied between zero (midnight) and unity (midday), thereby controlling the corresponding light level of the driving simulator. Fig. 1 shows the measured luminances at three positions in the traffic scene of the driving simulator as a function of the TOD value: 1) road (asphalt), 2) roadside (grass) and 3) sky. The traffic scene was modeled with an overcast sky outside the buildup area. The simulator car is driving with the headlamps on.

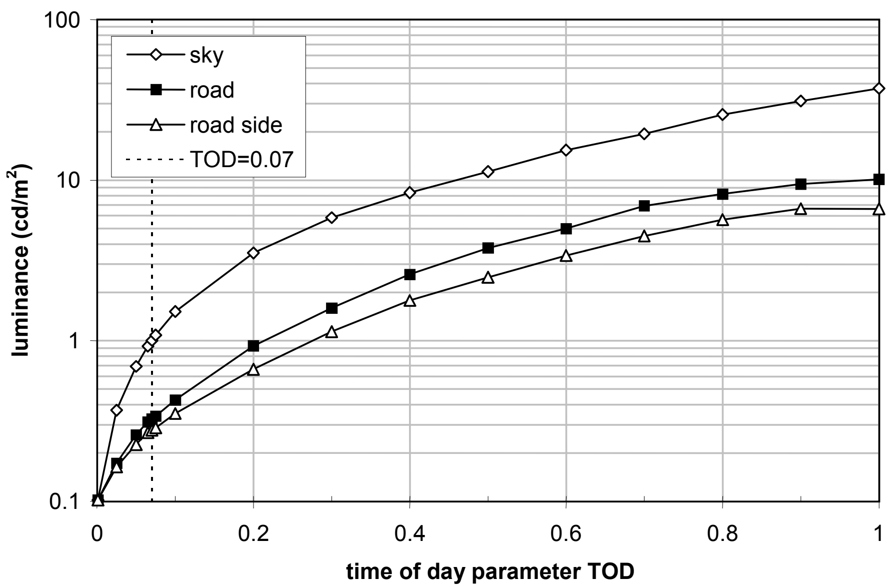



*Fig. 1 Luminances at three position (road, roadside, sky) in the traffic scene of the driving simulator as a function of "time-of- day" parameter TOD. TOD=0 corresponds to midnight, TOD=1 to midday. The proposed setting of 0.07 is indicated by the dotted (vertical) line.*

Between a TOD of 0.1 and 1 the luminances of the three positions increase in the same manner. Below a TOD of 0.1 the luminances converge to a common luminance of 0.1 cd/m$^2$, the lowest luminance level the driving simulator can reach. This, in fact, is straylight luminance caused by imperfections of the projector system.

After visual inspection of the traffic scenes in the driving simulator it appears that a TOD of 0.07 is a good compromise, representing the nighttime scene rather well, without getting into trouble with the limitations of the straylight luminance. The luminance at a TOD of 0.07 has nocturnal values. The luminances of the road, road side and sky at this TOD setting are 0.28 cd/$m^2$ 0.33 cd/$m^2$ and 1 cd/$m^2$, respectively In the literature, a ground luminance of 0.34 cd/$m^2$ is described as “deep twilight” and 0.034 cd/$m^2$ as “clear, moonlight”, measured in the real world (Douglas & Booker, 1977).

## 2.2 Fog

The fog was simulated in the driving simulator by setting the meteorological variables at the appropriate levels. We used previously measured recognition distances as a guideline (Godthelp, 1980). A dense fog with a meteorological visibility of 200 m decreases the shape recognition distance to about 60% and the symbol recognition distance to about 75% of the distance with good meteorological visibility (Z=15 km).

In a pilot experiment with two participants without IOL’s we found that a meteorological visibility setting in the driving simulator of 50 m causes an average reduction of the recognition distance of signs with a factor 1.6. The effect of fog on the detection distances is high; these distances decrease with a factor ten. The detection distances are limited to about 80 m. A visibility setting of 200 m was regarded as not a natural fog scene. In close consultation with AMO (Roland Pohl) we decided that a visibility setting of 60 m is a good compromise that will probably result in detection distances of about 100 m and a realistic natural fog modeling.

## 2.3 Glare

We have installed two glare sources. Each glare source consists of three white LEDs and a reflector built in a small lamp housing. The glare sources are fixed in the car above the dashboard at the left and the right from the line of sight. The size of the lamps is 2.5 cm x 2.5 cm. The angle between the (forward) line of sight and the glare source is 34 degrees to the left and 34 degrees to the right. The average illuminance of the combined glare sources at the eyes of the patient is 35 lx to 40 lx. The glare sources are switched on automatically when a glare condition is due. The positions and the illuminance level are chosen in close consultation with AMO (Roland Pohl).

This glare condition corresponds to a discomfort glare level of about 1.3 on the scale of De Boer, which can be described as somewhere between “unbearable” and “disturbing” (Schmidt-Clausen & Bindels, 1974; Alferdinck, 1996). The disability glare, expressed in terms of the veiling luminance is $40.10/33^2 = 0.35$ cd/$m^2$ (CIE, 2002). This veiling luminance will reduce the contrast in the scene and reduce the visibility distances of the objects.

In the pilot experiment we measured that the detection distance and the recognition distance both reduce with about 20%.

# 3 Traffic signs

When driving through the above described scenarios, the participants will be confronted with traffic signs listed in Fig. 2. The luminances of these traffic signs are modeled in such a way that the luminances and contrasts are as realistic as possible. Note that we have used four different colors, white, yellow, red, and blue. Since the participants in the experiment are from Germany and Italy, the text of the place name signs are in German or Italian.

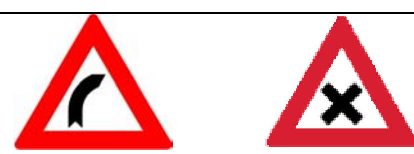
| Sign type | Picture |
|---|---|
| Advisory |  |
| Place-name |  |
| Warning for either a sharp curve or an intersection |  |

*Fig. 2 Traffic signs presented in the experiment*

We assumed that traffic signs are equipped with retroreflective sheeting, which generally is the case for almost all traffic signs on the road. Due to the retroreflection effect the signs will become visible in the light of the headlamps. The luminance of retroreflective traffic signs depends on the type of sheeting, the color of the sheeting, the luminous intensity of the headlamp, and the position of headlamp and drivers' eyes. For our experiment we assumed the signs equipped with Type II retroreflective sheeting and an 50-percentile European headlamp on a passenger car.

Fig. 3 shows the luminance of Type I and II retroreflective sheeting as a function of the distance between the driver's eyes and the sign (Godthelp, 1980). Due to the properties of the retroreflective sheeting and the position of the drivers' eyes, headlamps and traffic sign, the luminance is zero at a short distance, reaches a maximum between 50 m and 100 m and decreases to lower values at large distances. Note that the maximum luminance of Type II is larger than the maximum luminance of Type I, and occurs at a larger distance.

The curve for Type II retroreflective material was modeled in the driving simulator. However, after visual inspection of the simulator screen it appeared that the signs were unnaturally dark at distances lower than 50 m. The signs appeared black against the relatively light sky which is caused by the limited night performance of the simulator. Therefore we decided to leave the luminance at the maximum level for distances lower than 100 m (Fig. 3).

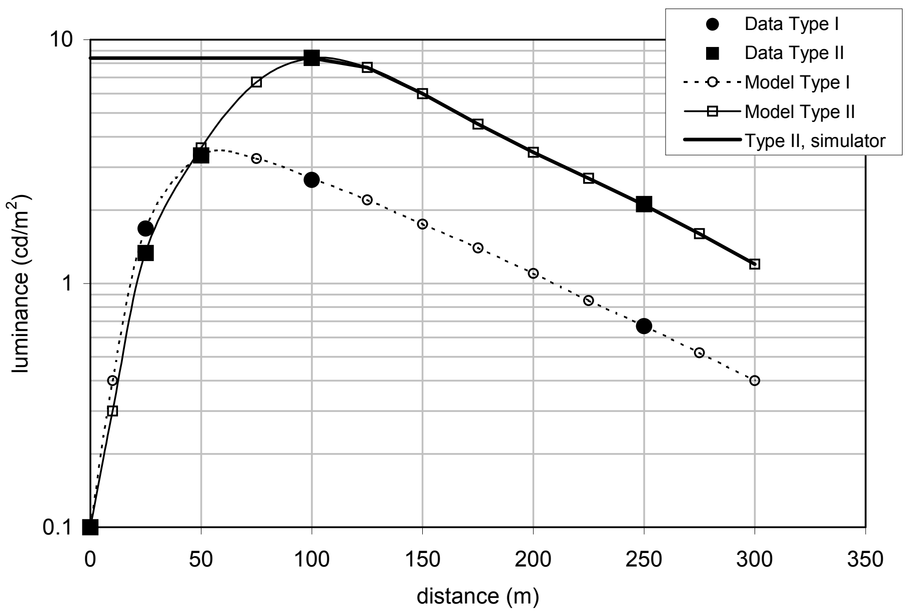



*Fig. 3 Luminances of the color white of Type I and II retroreflecting traffic signs as a function of viewing distance. Data = measured data (Godthelp, 1980). Model = interpolated data points. Simulator = data for use in the driving simulator.*

The sign dimensions are derived from the size requirements for signs on a Dutch rural road with a maximum speed of 80 km/h (NVV, 2001). For such a road the circular sign has a diameter of 800 mm, a triangular shaped sign has a side of 900 mm and a square shaped sign has a side length of 800 mm. The place name signs has a height of 340 mm.

The resolution of the projection system of the driving simulator is limited to 2,1 arcminutes (1280 x 1024 pixels, width = 45 degrees, 5 degrees overlap, distance eye-screen = 3.75 m). The resolution of the human eye is about 1 arcminute. Therefore the signs shall be enlarged by about a factor two in order to end up with recognition distances similar the recognition distances measured in practice.

The recognition distances were measured in the driving simulator in a pilot experiment. The results are listed in Table I and compared with the recognition distances of traffic signs in practice (Godthelp, 1980). The recognition distances on the road assume a Landolt-C visual acuity of 1 (similar to Snellen 20/20), being the 85-percentile value of the visual acuity of road users.

In order to be comparable to the distances measured on the road, the distances in the simulator are recalculated for a Landolt-C acuity of 1. Symbol recognition on the road can be compared to recognition in the simulator (Table I). Given the spread in the simulator data (two subjects) it can be concluded that the data correspond reasonably well. The detection distances are much higher than the shape recognition distances. This difference can be understood knowing that at the detection distance the shape not yet can be recognized.

*Table I. Distances for the shape and symbol recognition of traffic signs in practice (road) and the detection and recognition of traffic signs in the TNO driving simulator (simulator). Figures between brackets are the standard deviations.*

| Sign | Distance (m) | | | |
|---|---|---|---|---|
| | Road | | Simulator | |
| | Shape | Symbol | Detection | Recognition |
| Advisory | 182 | - | 564 (44) | 94 (11) |
| Warning | 253 | 56 | 475 (99) | 88 (23) |
| Speed limit | 177 | 85 | 300 | 84 |
| Guide | - | 112 | 516 (109) | 59 (46) |

# 4 Hazardous events

The hazardous events in the experiment consist of a pedestrian looking either to the left or the right, a traffic cone, or a suitcase (see Fig. 4).

| | |
|---|---|
|  | Pedestrian |
|  | Traffic Cone |
|  | Suitcase |

*Fig. 4 Hazardous events presented in the experiment*

The luminances of these object were calculated as follows.
First, the headlamp luminous intensities (I) in the direction of the objects were calculated using the data for a European low beam (Sivak et al., 1994), assuming that the object appears right in front of the car at distances (d) between 10 m and 300 m. Secondly, the illuminance (E) at the objects was calculated using the inverse square law ($E=I/d^2$). Finally, the luminance (L) of the objects was calculated using the reflection properties (luminance factor β) of the objects ($L=\beta E/\pi$). The luminance factor of the fluorescent orange of the cone was 0.4, based on the requirements for color "fluorescent orange-red" of the international standard for fluorescent materials (CEN, 2003). The luminance factor of the shirt of the pedestrian was set at 0.8 and the luminance factor of the brown suitcase was set at 0.1. The calculated luminances were multiplied by a calibration factor in order to get realistic recognition distances in the driving simulator. The results are plotted in Fig. 5.

Note that the luminances of the hazardous objects increase with decreasing distance, and are lower than the luminances of retroreflecting traffic signs for distances more than 70 m. The luminance of the T-shirt of the pedestrian on the roadside is much lower than the luminance of the other objects on the road. This is due to the properties of the headlamp beam. At short distances the luminances of the cone and suitcase are limited by the maximum luminance of the driving simulator (about 20 $cd/m^2$).

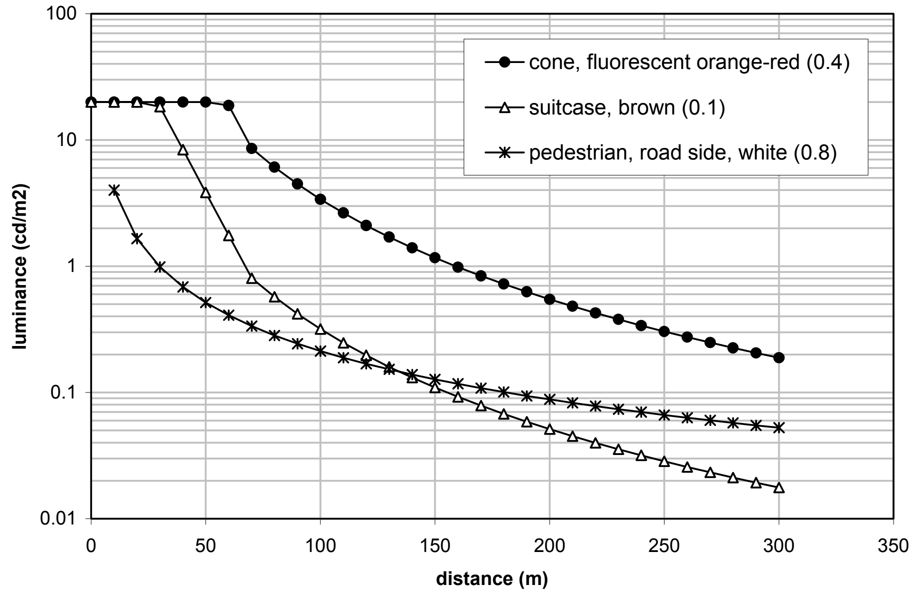



*Fig. 5 Luminances of three objects, illuminated by car headlamps, modeled in the driving simulator, as a function of viewing distance; two objects at the road surface (cone, fluorescent orange-red; suitcase, brown) and a white T-shirt of a pedestrian at the road side.*

The color of the cone was derived from the international standard, being the color in the center of the allowed color box (CIE chromaticity coordinates x=0.593 and y=0.363).

After the modeling the detection and recognition distances of the objects for the hazardous event were measured in the same pilot study with two participants. The results are listed in Table II. Note that the pedestrian is detected at a rather large distance. This is due to the fact that the pedestrian is partly perceived as a silhouette against the sky. The pedestrian is recognized (recognition of the face orientation) at a rather short distance of about 50 m. The cone and the suitcase are detected only at distances between 40 m and 80 m. The recognition distance of these objects is about 50% of the detection distance. Note that due to its dark brown color, the suitcase has much shorter distances than the cone. The short detection and recognition distances of the cone and the suitcase are caused by the European headlamp shape which has a light-dark cut-of at about 60 m (Sivak et al., 1994).

*Table II. Detection and recognition of the objects used for the hazardous events in the TNO driving simulator, measured in a pilot experiment. The average standard deviations is about 50%..*

| Object | Detection distance (m) | Recognition distance (m) |
|---|---|---|
| Pedestrian | 206 | 49 |
| Cone | 75 | 45 |
| Suitcase | 39 | 17 |

# 5 Pupil measurements

During the runs in the driving simulator the pupil diameter is recorded continuously. The pupil measurement device consists of a small camera and an IR illuminator mounted on a baseball cap (see Fig. 6). During the simulator drives one of the patient's eyes will be patched with a black eye patch. So, the performance and pupil size during the drives will be only of one of the eyes. Half of the drives the patients drove with the left eye and the other half with the right eye. The raw measurements are done in arbitrary pixel units. Thus, intra-subject relative pupil size is accurately recorded for all test conditions. However, each patient's absolute pupil size will be calibrated for as follows. We will measure the size of a calibration target, which is placed on the relevant (closed) eye of each subject. The calibration target consists of black circle of 10 mm diameter printed on a white thin strip (2 cm x 10 cm). Knowing the camera field of view, the diameter of the calibration target, strip thickness and an estimation of the thickness of the eyelid, the absolute pupil diameter can be calculated.


*Fig. 6. Participant wearing baseball cap with pupil size measurement equipment.*

# 6 Experimental design

The experiment follows a within subjects design. This means that every participant drives the 3 different scenarios in two conditions (once with each eye). After consultation with AMO it was decided that in the nighttime clear weather condition, *all* signs and hazards are presented in a random order. In the glare and fog conditions, *half* of the signs will be presented in a random order to keep driving time at a minimum. All six conditions are split in 2 drives in the simulator to reduce fatigue and allow the subjects to rest. So every participant will make 12 different drives in the simulator. In Annex 1, Table III, the distribution of the events (traffic signs and hazardous events) within each condition is described in detail.

These drives or conditions are balanced as follows:
- Half of the participants start driving with the right eye, the other half starts driving with the left eye.
- The order of the conditions (per participant) is the same for each eye.
- The order of the conditions (between participants) is different. The Latin-square method is used to balance the order of conditions over participants.

In Annex 2, Table IV, the complete table with the condition order of every participant is shown. Please note that participant 1 to 16 start out with their right eye and participant 17 to 32 start out with their left eye. Participant number 33 to 37 are reserve numbers for starting out with the right eye. Participant number 38 to 42 are reserve numbers for starting out with the left eye.

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# 8 ANNEX 1

*Table III. Experimental conditions. Ped. Left, Ped. Right = pedestrian looking to the left or right. Baseline = condition with no sign or hazard event, which is used to measure the baseline driving behaviour.*

| | | | | | |
|---|---|---|---|---|---|
| **Condition 1A: nighttime clear weather** | | | | | |
| Parking sign | Ped. Left | Aachen Süd | Aachen Ost | Baseline | Traffic cone |
| **Condition 1B: nighttime clear weather** | | | | | |
| Suitcase | Baseline | Curve sign | Ped. Right | Inters. Sign | Straight sign |
| **Condition 2A: nighttime clear weather** | | | | | |
| Curve sign | Baseline | Parking sign | Suitcase | Aachen Süd | Ped. left |
| **Condition 2B: nighttime clear weather** | | | | | |
| Aachen Ost | Traffic cone | Ped. Right | Inters. sign | Straight sign | Baseline |
| **Condition 3A: Fog right eye** | | | | | |
| Aachen Süd | Baseline | Suitcase | Ped. Left | Straight sign | |
| **Condition 3B: Fog right eye** | | | | | |
| Traffic cone | Ped. Right | Baseline | Curve sign | | |
| **Condition 4A: Fog left eye** | | | | | |
| Baseline | Parking sign | Ped. Left | Suitcase | Aachen Ost | |
| **Condition 4B: Fog left eye** | | | | | |
| Ped. Right | Inters. sign | Traffic cone | Baseline | | |
| **Condition 5A: Glare right eye** | | | | | |
| Ped. Left | Traffic cone | Straight sign | | Baseline | |
| **Condition 5B: Glare right eye** | | | | | |
| Baseline | Ped. Right | Aachen Süd | Curve sign | Suitcase | |
| **Condition 6A: Glare left eye** | | | | | |
| Parking sign | Aachen Ost | Baseline | | Ped. Right | |
| **Condition 6B: Glare left eye** | | | | | |
| Baseline | Traffic cone | Ped. Left | Suitcase | Inters. Sign | |

# 9 ANNEX 2

*Table IV. Order of the experimental conditions for each patient (pp). For experimental condition see Table III.*

| pp | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1a | 3a | 5a | 1b | 3b | 5b | 2a | 4a | 6a | 2b | 4b | 6b |
| 2 | 5b | 1a | 3a | 5a | 1b | 3b | 6b | 2a | 4a | 6a | 2b | 4b |
| 3 | 3b | 5b | 1a | 3a | 5a | 1b | 4b | 6b | 2a | 4a | 6a | 2b |
| 4 | 1b | 3b | 5b | 1a | 3a | 5a | 2b | 4b | 6b | 2a | 4a | 6a |
| 5 | 5a | 1b | 3b | 5b | 1a | 3a | 6a | 2b | 4b | 6b | 2a | 4a |
| 6 | 3a | 5a | 1b | 3b | 5b | 1a | 4a | 6a | 2b | 4b | 6b | 2a |
| 7 | 5b | 3b | 1b | 5a | 3a | 1a | 6b | 4b | 2b | 6a | 4a | 2a |
| 8 | 1a | 5b | 3b | 1b | 5a | 3a | 2a | 6b | 4b | 2b | 6a | 4a |
| 9 | 3a | 1a | 5b | 3b | 1b | 5a | 4a | 2a | 6b | 4b | 2b | 6a |
| 10 | 5a | 3a | 1a | 5b | 3b | 1b | 6a | 4a | 2a | 6b | 4b | 2b |
| 11 | 1b | 5a | 3a | 1a | 5b | 3b | 2b | 6a | 4a | 2a | 6b | 4b |
| 12 | 3b | 1b | 5a | 3a | 1a | 5b | 4b | 2b | 6a | 4a | 2a | 6b |
| 13 | 1a | 5a | 3a | 1b | 5b | 3b | 2a | 6a | 4a | 2b | 6b | 4b |
| 14 | 3b | 1a | 5a | 3a | 1b | 5b | 4b | 2a | 6a | 4a | 2b | 6b |
| 15 | 5b | 3b | 1a | 5a | 3a | 1b | 6b | 4b | 2a | 6a | 4a | 2b |
| 16 | 1b | 5b | 3b | 1a | 5a | 3a | 2b | 6b | 4b | 2a | 6a | 4a |
| 17 | 2a | 4a | 6a | 2b | 4b | 6b | 1a | 3a | 5a | 1b | 3b | 5b |
| 18 | 6b | 2a | 4a | 6a | 2b | 4b | 5b | 1a | 3a | 5a | 1b | 3b |
| 19 | 4b | 6b | 2a | 4a | 6a | 2b | 3b | 5b | 1a | 3a | 5a | 1b |
| 20 | 2b | 4b | 6b | 2a | 4a | 6a | 1b | 3b | 5b | 1a | 3a | 5a |
| 21 | 6a | 2b | 4b | 6b | 2a | 4a | 5a | 1b | 3b | 5b | 1a | 3a |
| 22 | 4a | 6a | 2b | 4b | 6b | 2a | 3a | 5a | 1b | 3b | 5b | 1a |
| 23 | 6b | 4b | 2b | 6a | 4a | 2a | 5b | 3b | 1b | 5a | 3a | 1a |
| 24 | 2a | 6b | 4b | 2b | 6a | 4a | 1a | 5b | 3b | 1b | 5a | 3a |
| 25 | 4a | 2a | 6b | 4b | 2b | 6a | 3a | 1a | 5b | 3b | 1b | 5a |
| 26 | 6a | 4a | 2a | 6b | 4b | 2b | 5a | 3a | 1a | 5b | 3b | 1b |
| 27 | 2b | 6a | 4a | 2a | 6b | 4b | 1b | 5a | 3a | 1a | 5b | 3b |
| 28 | 4b | 2b | 6a | 4a | 2a | 6b | 3b | 1b | 5a | 3a | 1a | 5b |
| 29 | 2a | 6a | 4a | 2b | 6b | 4b | 1a | 5a | 3a | 1b | 5b | 3b |
| 30 | 4b | 2a | 6a | 4a | 2b | 6b | 3b | 1a | 5a | 3a | 1b | 5b |
| 31 | 6b | 4b | 2a | 6a | 4a | 2b | 5b | 3b | 1a | 5a | 3a | 1b |
| 32 | 2b | 6b | 4b | 2a | 6a | 4a | 1b | 5b | 3b | 1a | 5a | 3a |
| 33 | 1a | 3a | 5a | 1b | 3b | 5b | 2a | 4a | 6a | 2b | 4b | 6b |
| 34 | 5b | 1a | 3a | 5a | 1b | 3b | 6b | 2a | 4a | 6a | 2b | 4b |
| 35 | 3b | 5b | 1a | 3a | 5a | 1b | 4b | 6b | 2a | 4a | 6a | 2b |
| 36 | 1b | 3b | 5b | 1a | 3a | 5a | 2b | 4b | 6b | 2a | 4a | 6a |
| 37 | 5a | 1b | 3b | 5b | 1a | 3a | 6a | 2b | 4b | 6b | 2a | 4a |
| 38 | 2a | 4a | 6a | 2b | 4b | 6b | 1a | 3a | 5a | 1b | 3b | 5b |
| 39 | 6b | 2a | 4a | 6a | 2b | 4b | 5b | 1a | 3a | 5a | 1b | 3b |
| 40 | 4b | 6b | 2a | 4a | 6a | 2b | 3b | 5b | 1a | 3a | 5a | 1b |
| 41 | 2b | 4b | 6b | 2a | 4a | 6a | 1b | 3b | 5b | 1a | 3a | 5a |
| 42 | 6a | 2b | 4b | 6b | 2a | 4a | 5a | 1b | 3b | 5b | 1a | 3a |