Luminous Intensity for Traffic Signals: A Scientific Basis for Performance Specifications

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Appendices to Final Report

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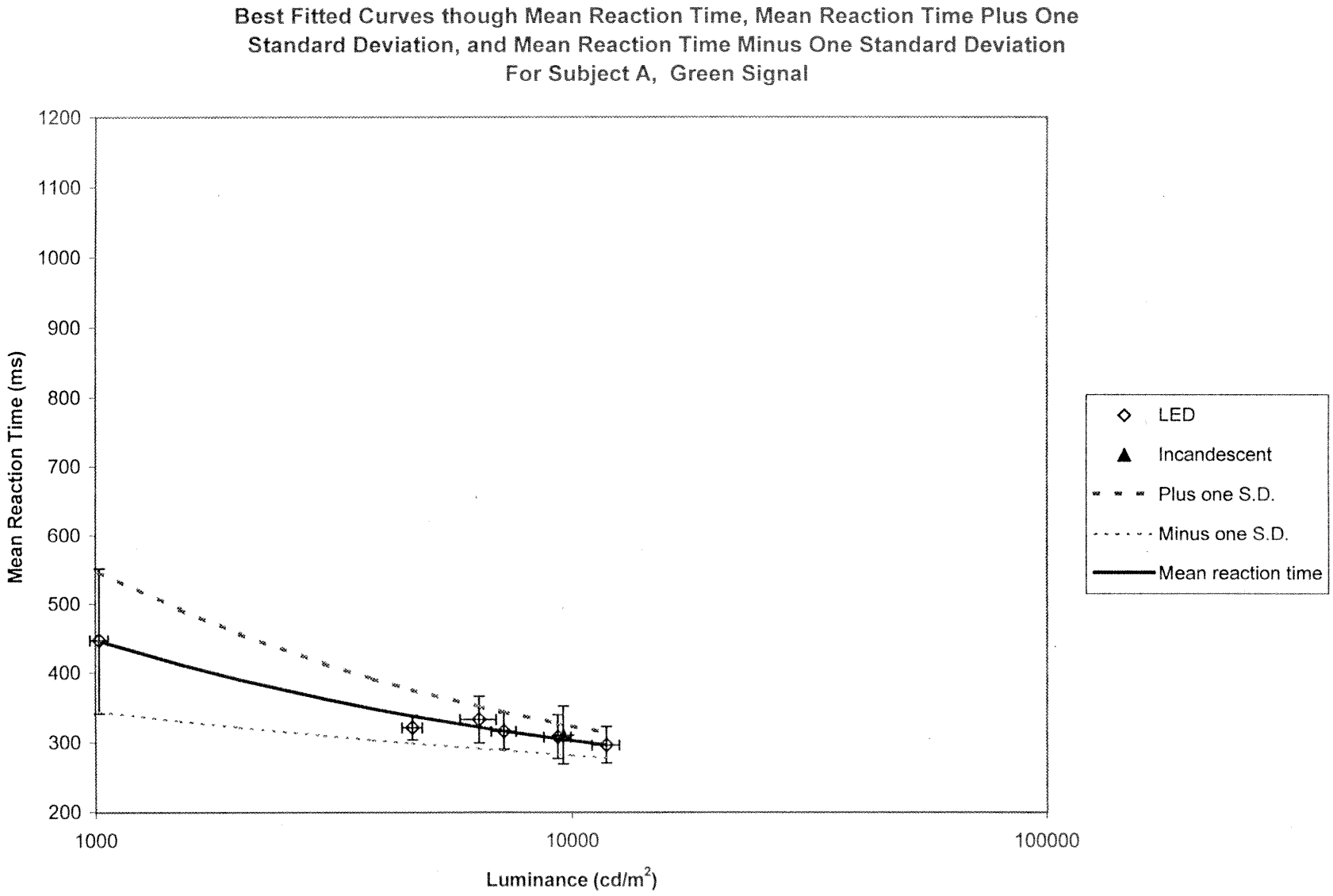
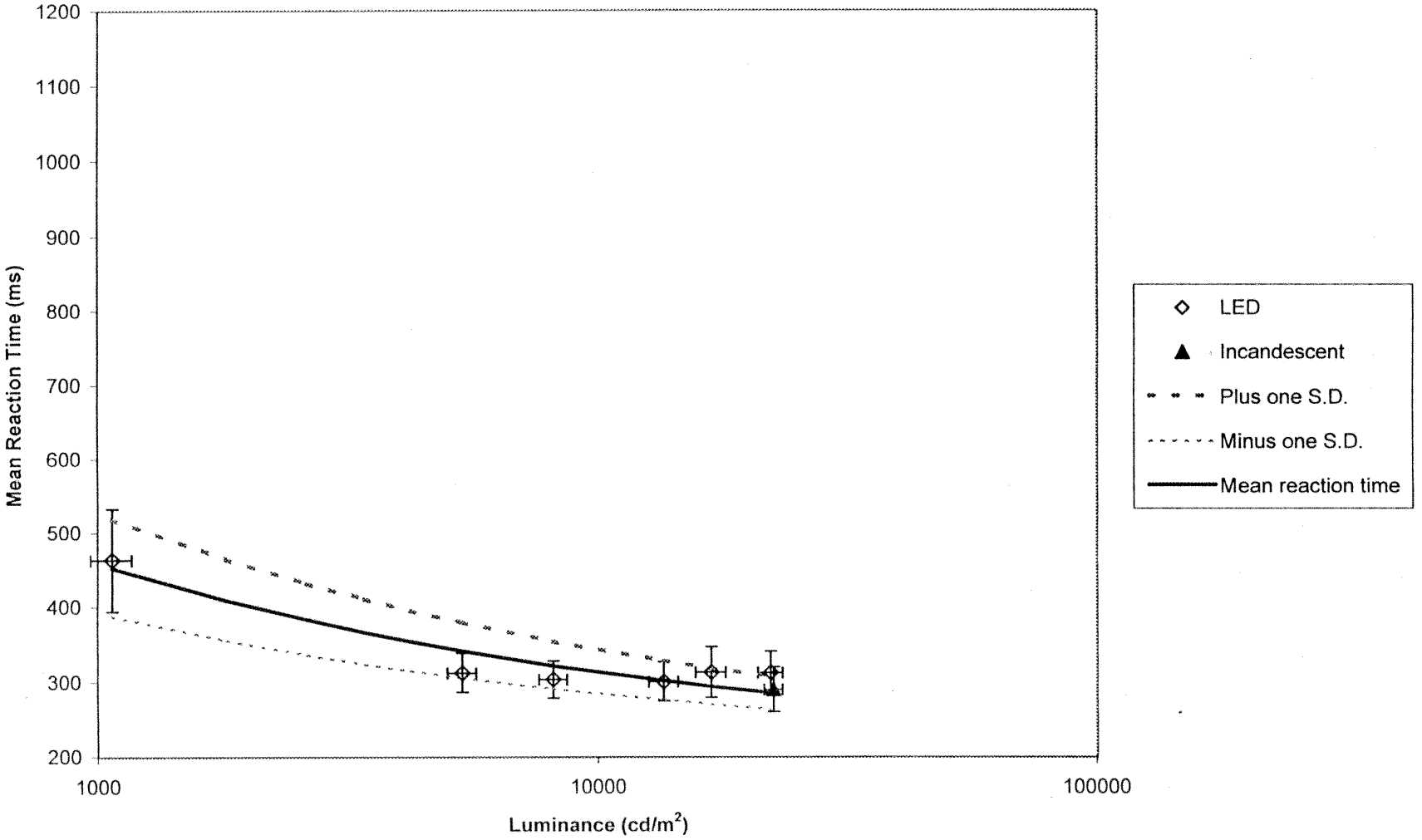
Appendix 1

Mean Reaction Times for Individual Subjects

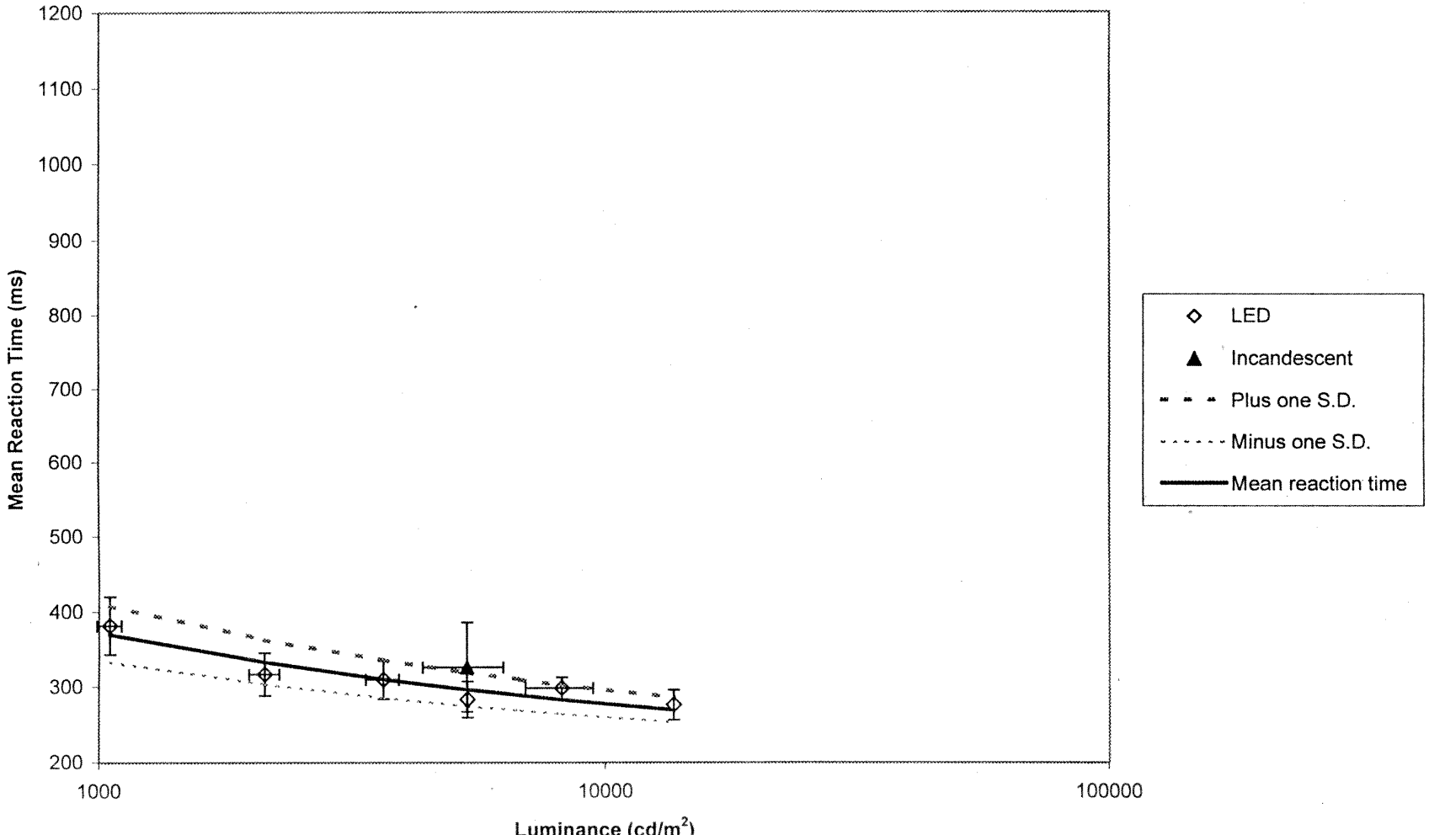
The following figures show the mean reaction time plotted against the signal luminance, for each subject when viewing each combination of luminance and color used. The y-axis error bars correspond to one standard deviation about the mean reaction time. The x-axis error bars correspond to one standard deviation about the mean measured luminance. The x-axis error bars are only given for the measurements made in the first experiment. For that study, the luminance of the signals was measured in several different ways and the results averaged. No additional luminance measurements were made in the third experiment, the relationship between mean measured luminance and current through the LED established in the first experiment being used to predict the current required to achieve the desired signal luminance in the third experiment. The three curves in each figure are power law fits through the mean reaction times, the mean reaction times plus one standard deviation and the mean reaction time minus one standard deviation. The power law fits through the mean reaction times plus and minus one standard deviation have been calculated to provide a sensitivity test for the normalized equations predicting the percentage change in reaction time (See Appendix 3).


Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject A, Green Signal
Mean Reaction Time (ms)
1200
1100
1000
900
800
700
600
500
400
300
200
1000
10000
100000
Luminance (cd/m2)
LED
Incandescent
Plus one S.D.
Minus one S.D.
Mean reaction time

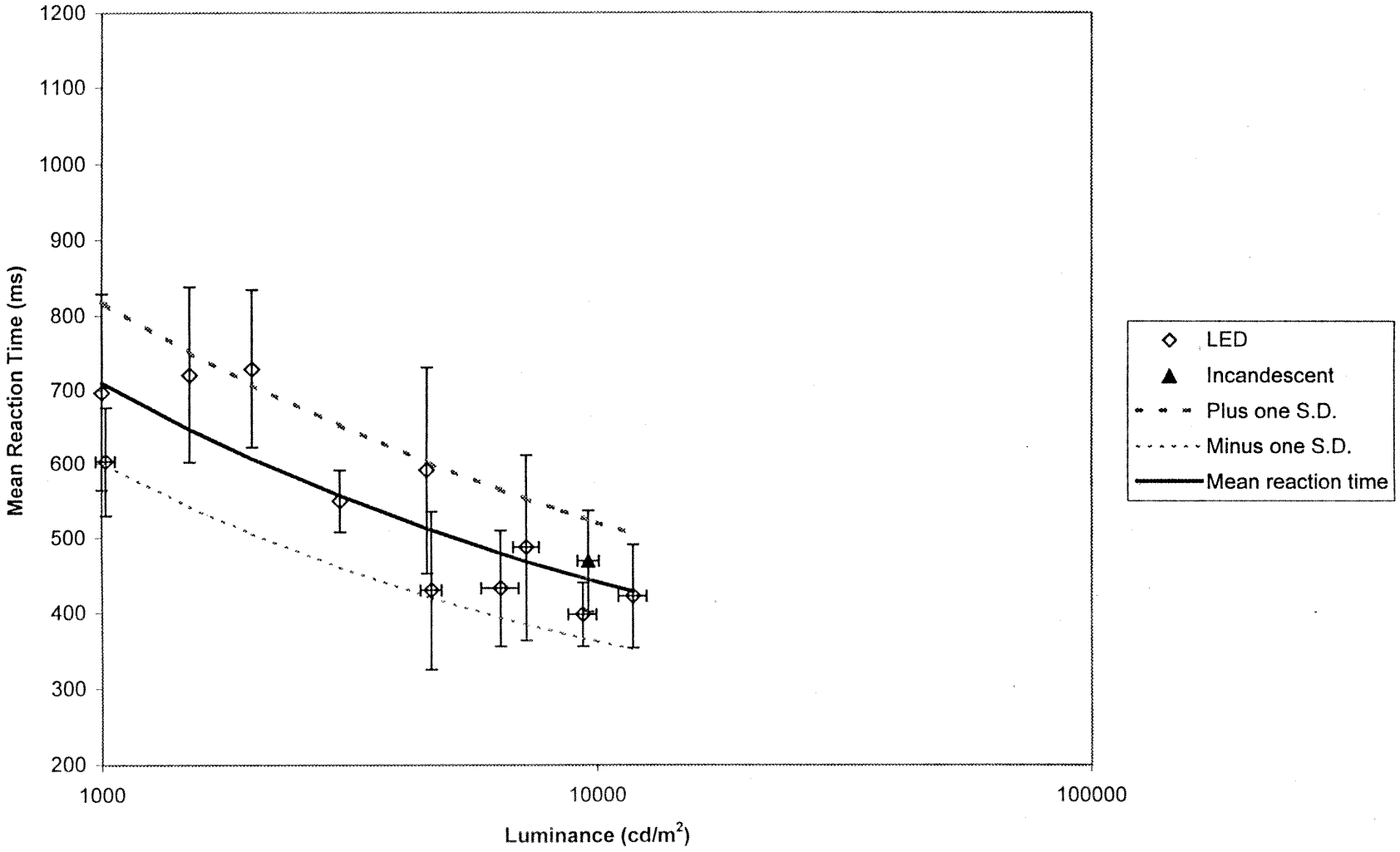
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject A, Yellow Signal



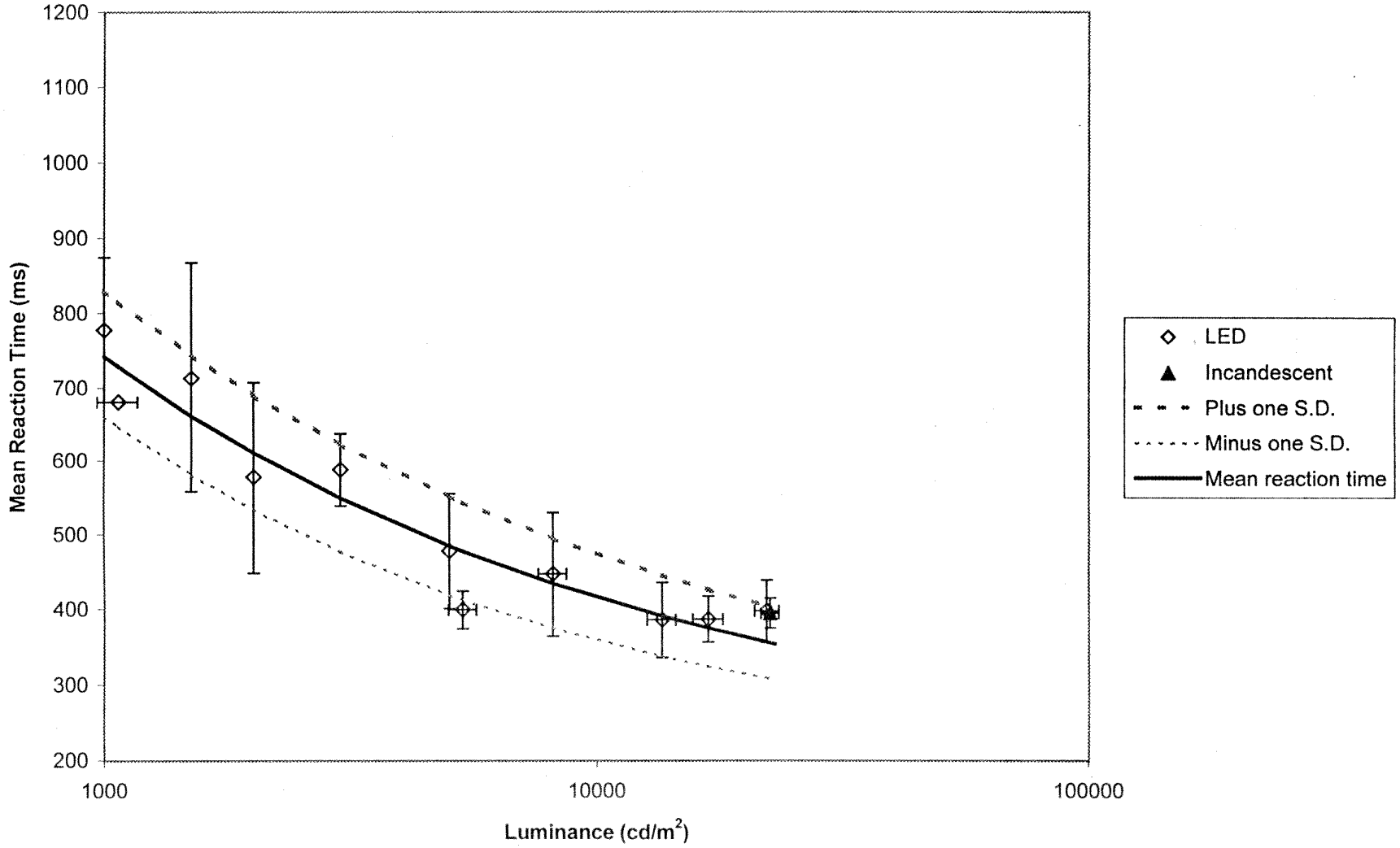
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject A, Red Signal



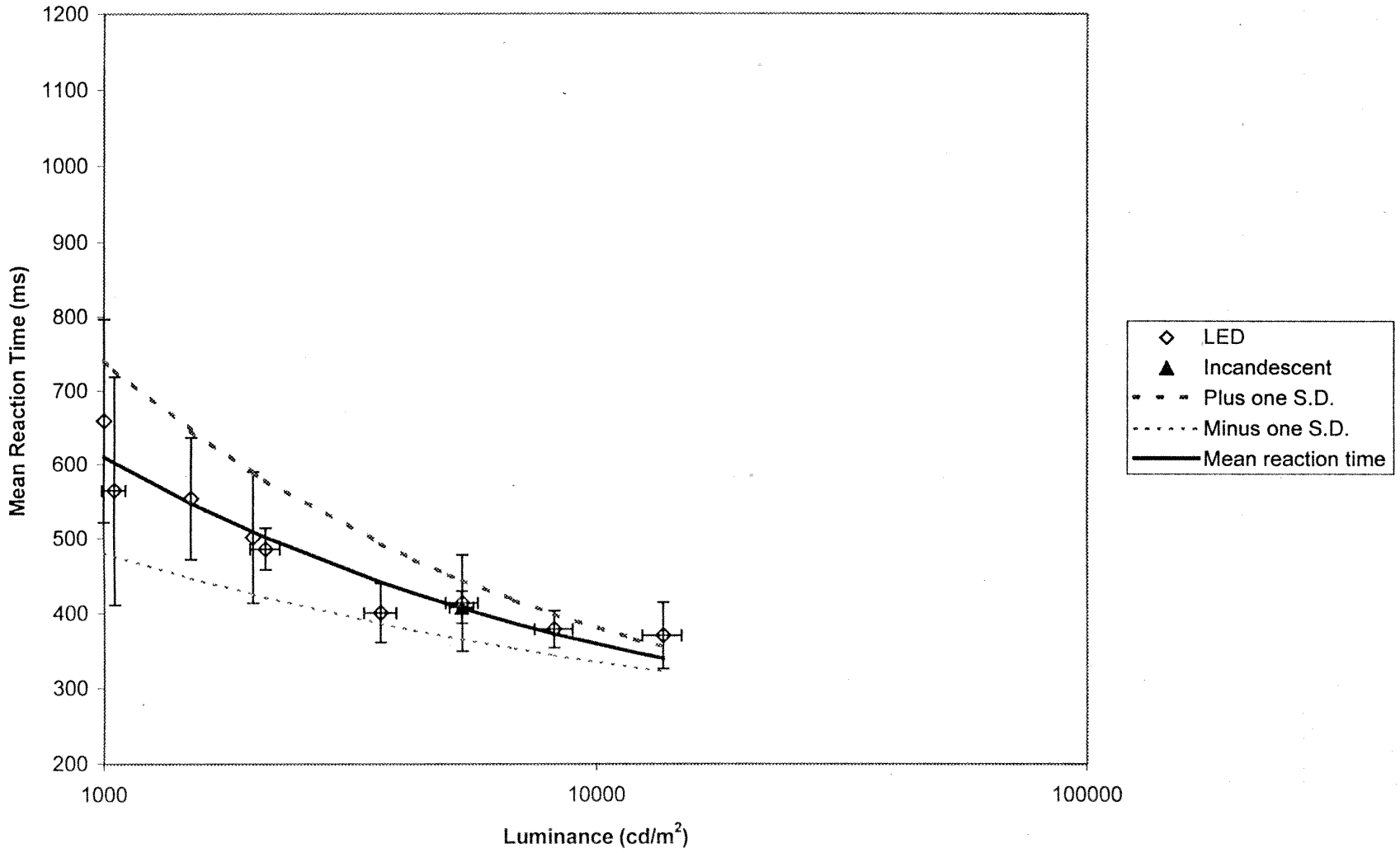
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject B, Green Signal



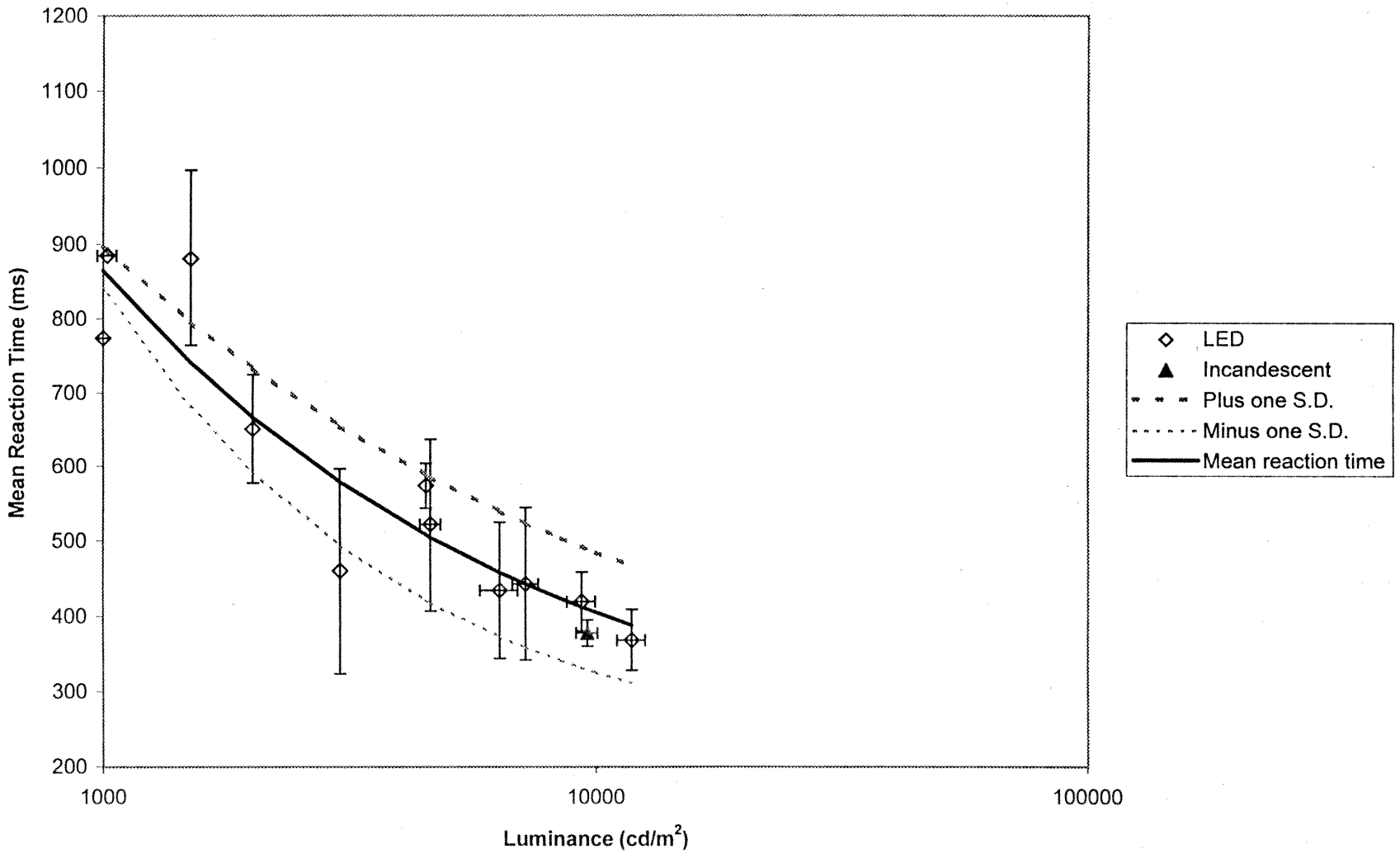
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject B, Yellow Signal



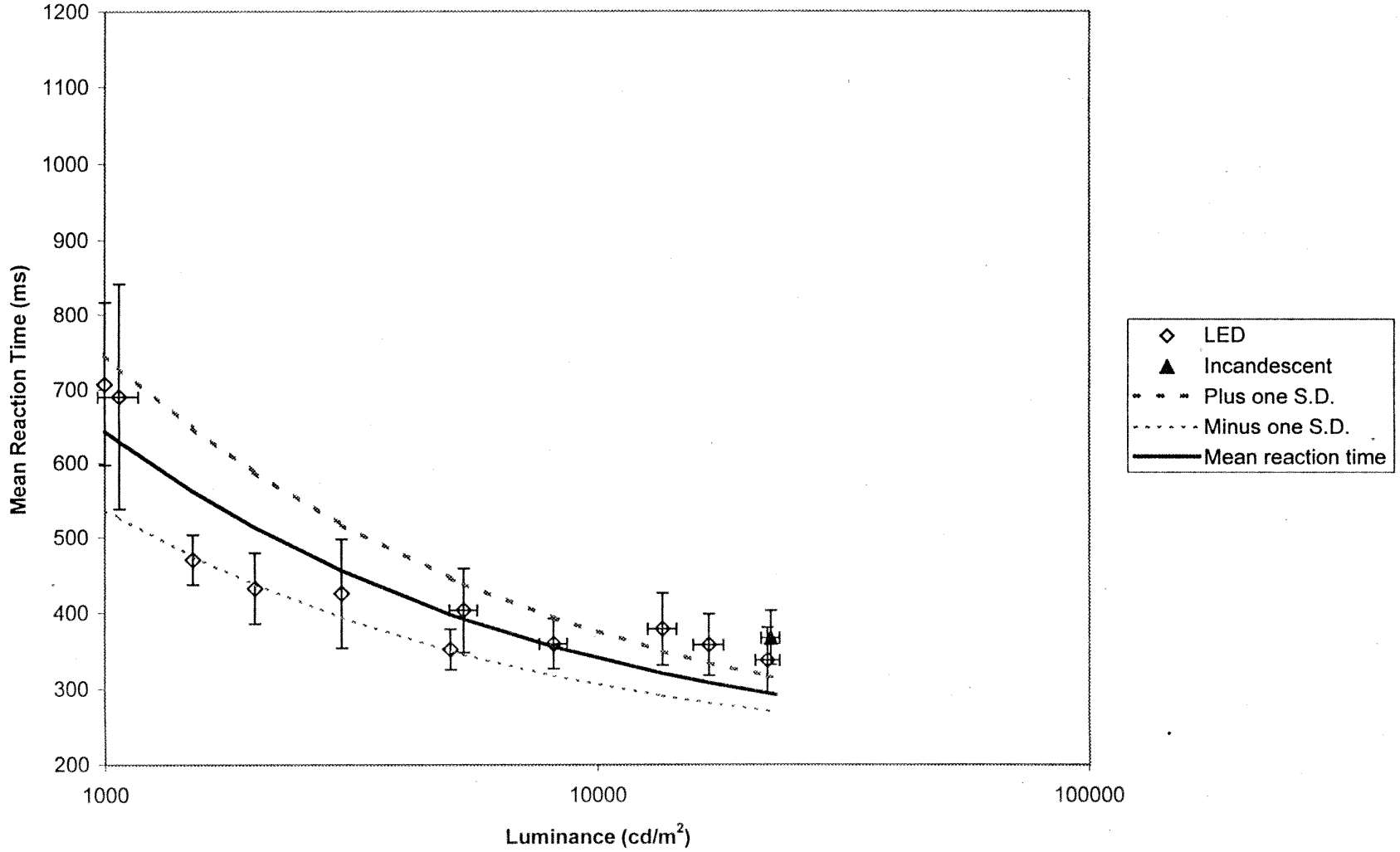
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject B, Red Signal



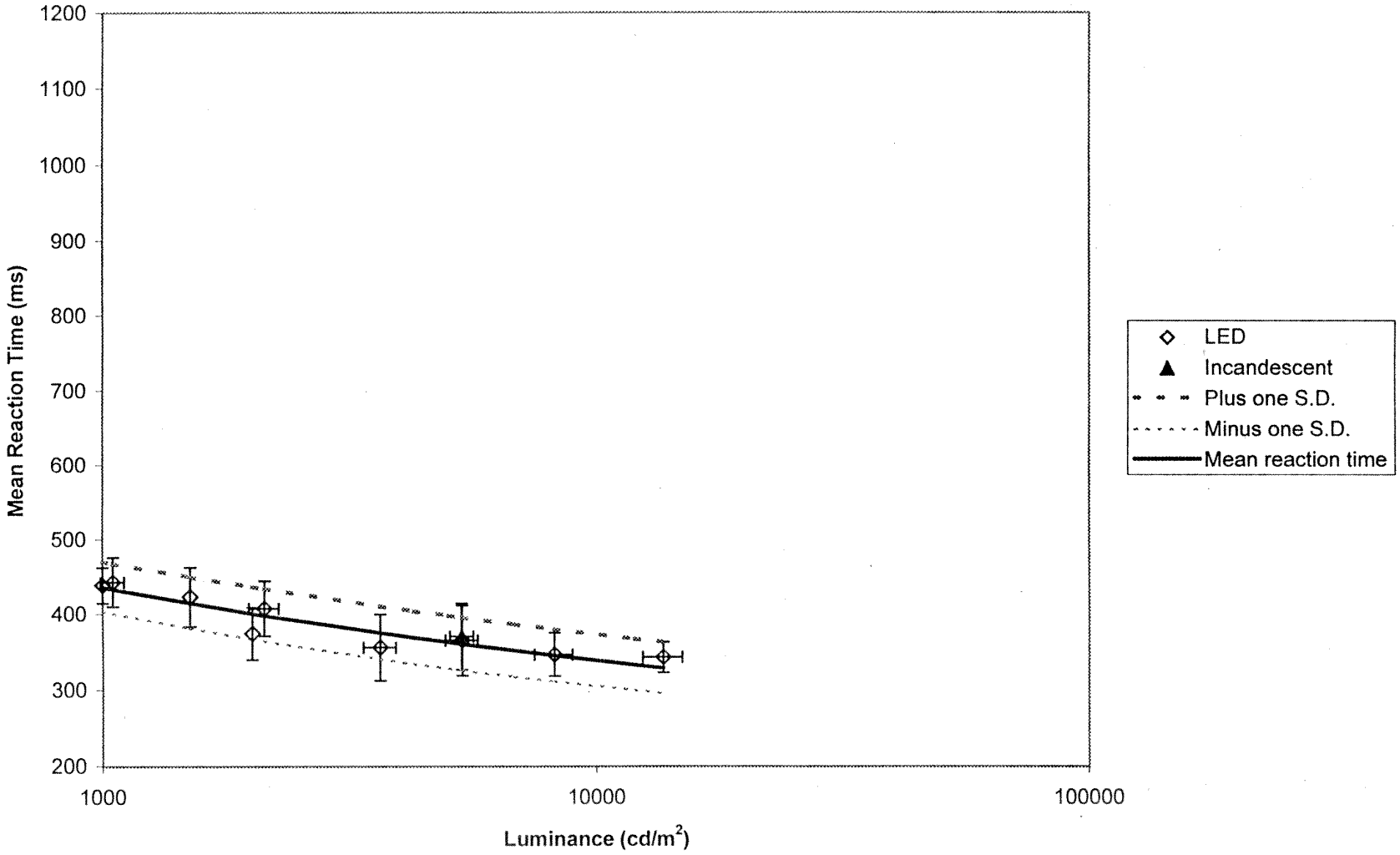
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject C, Green Signal



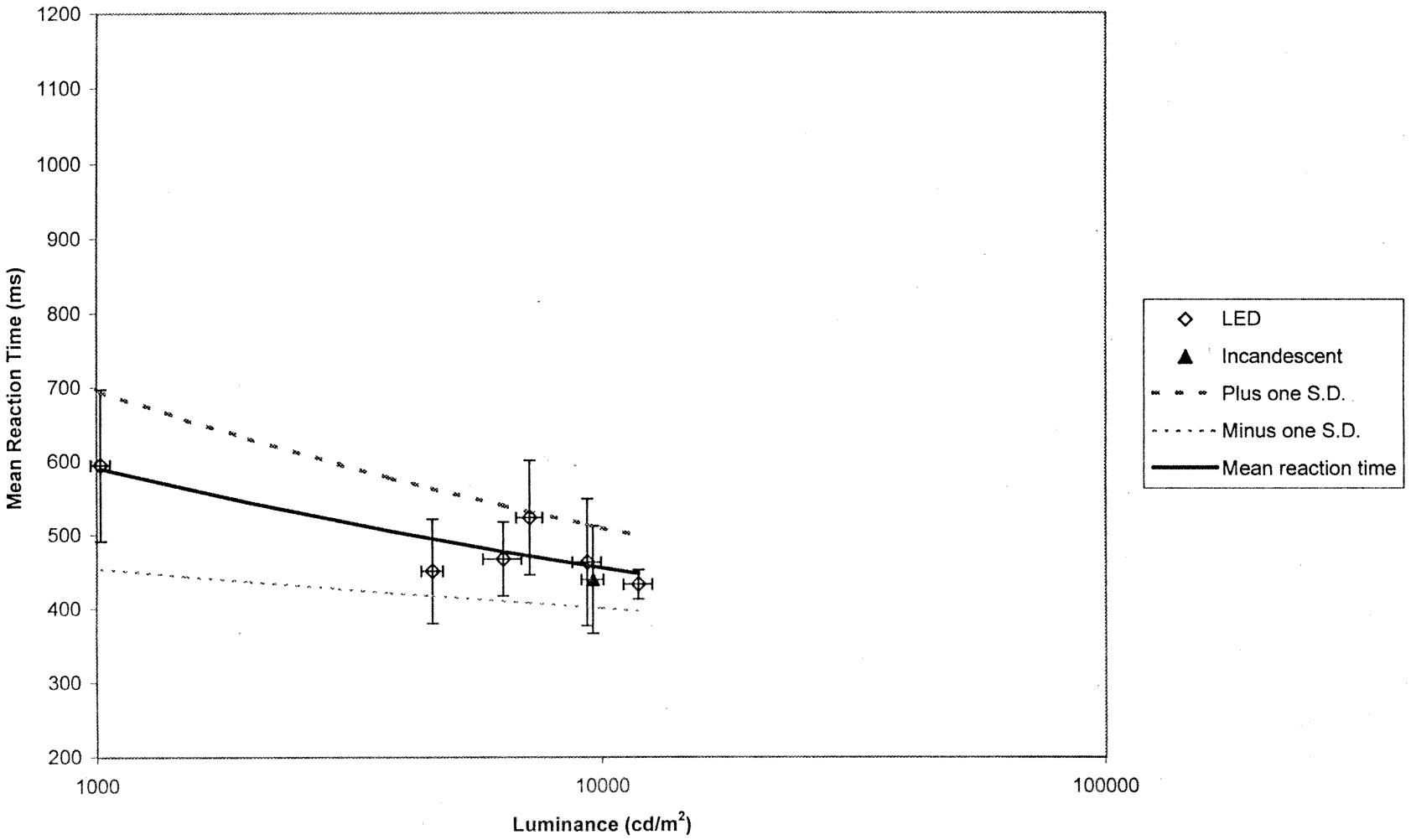
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject C, Yellow Signal



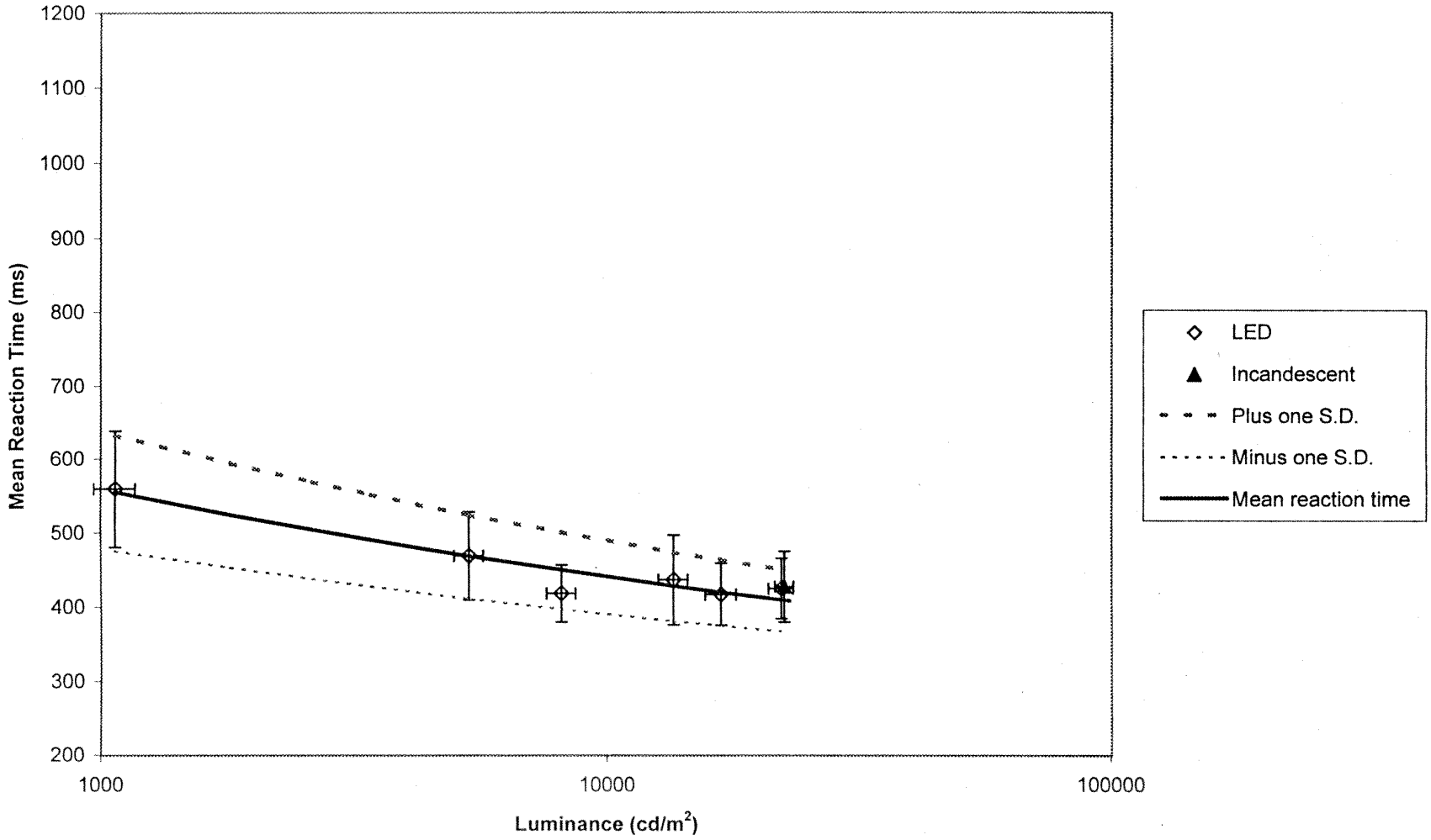
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject C, Red Signal



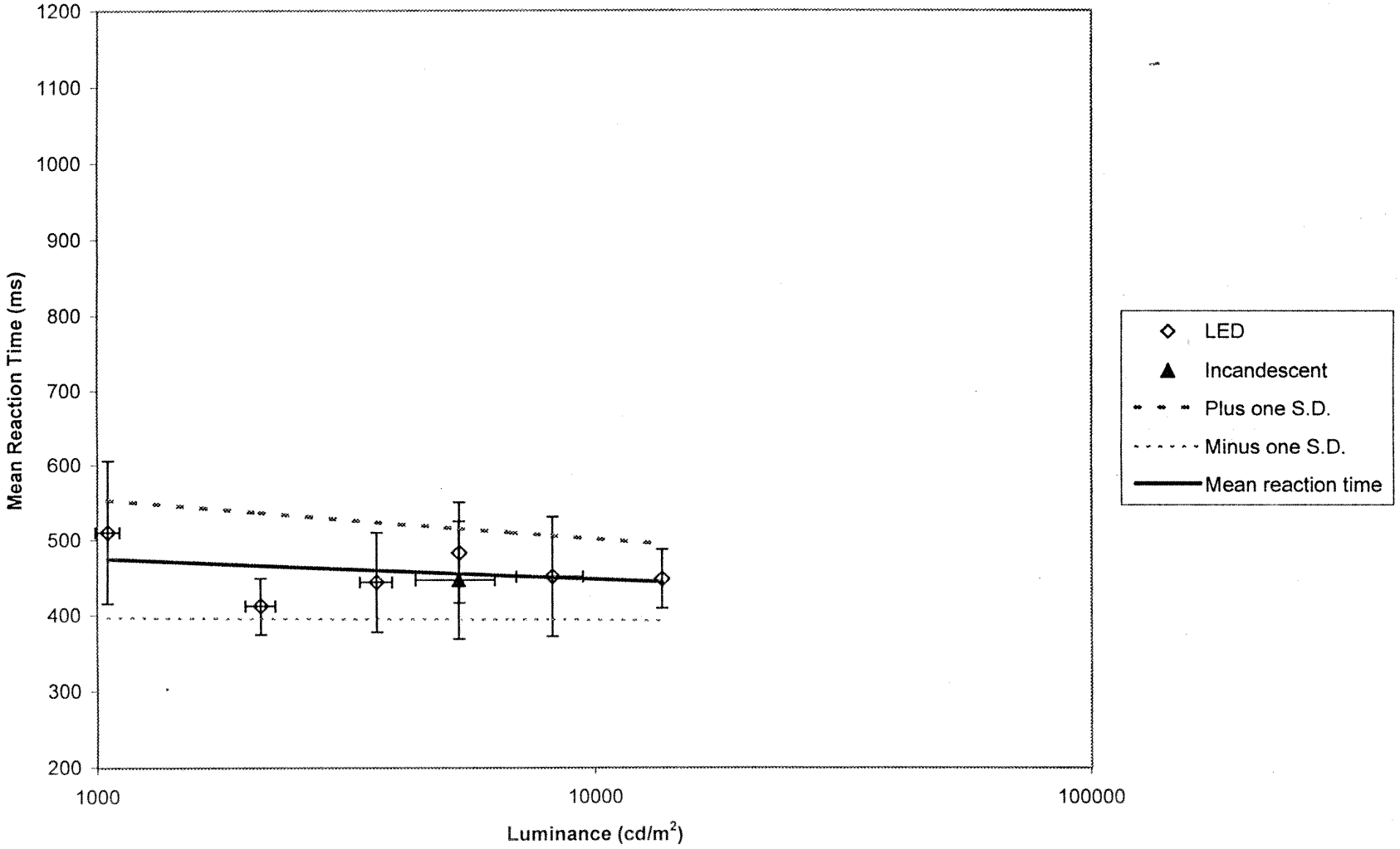
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Green Signal



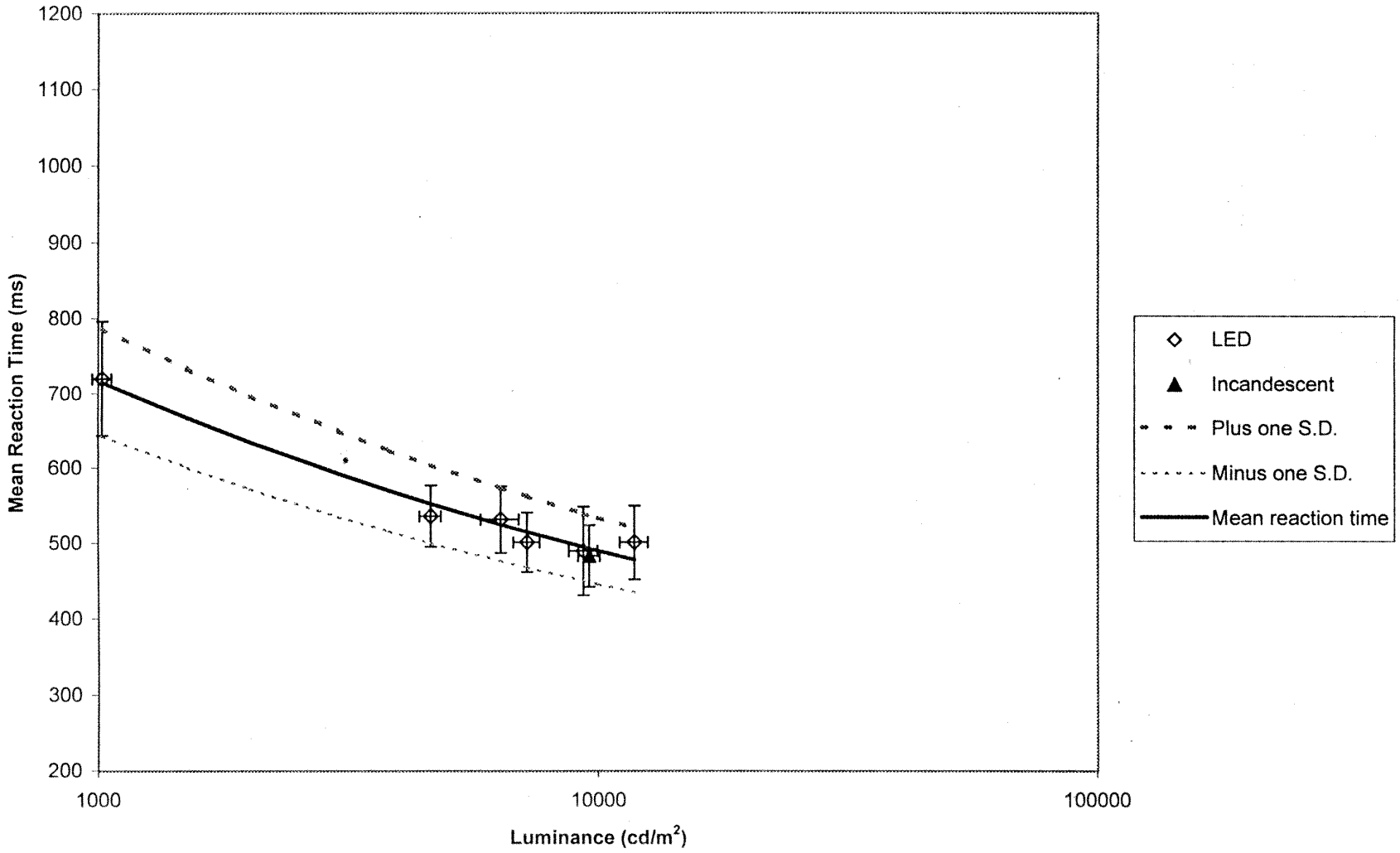
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Yellow Signal



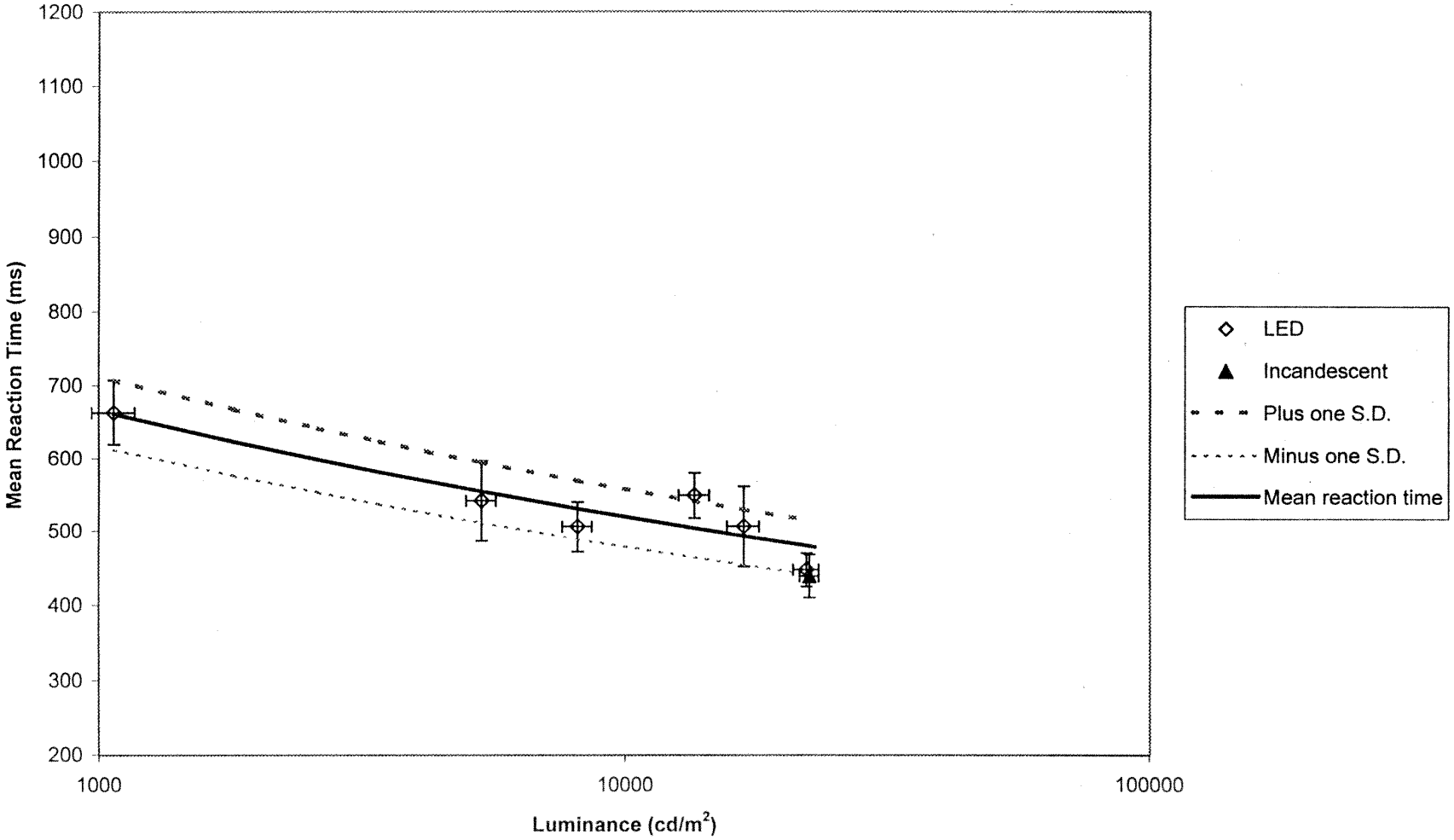
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject D, Red Signal



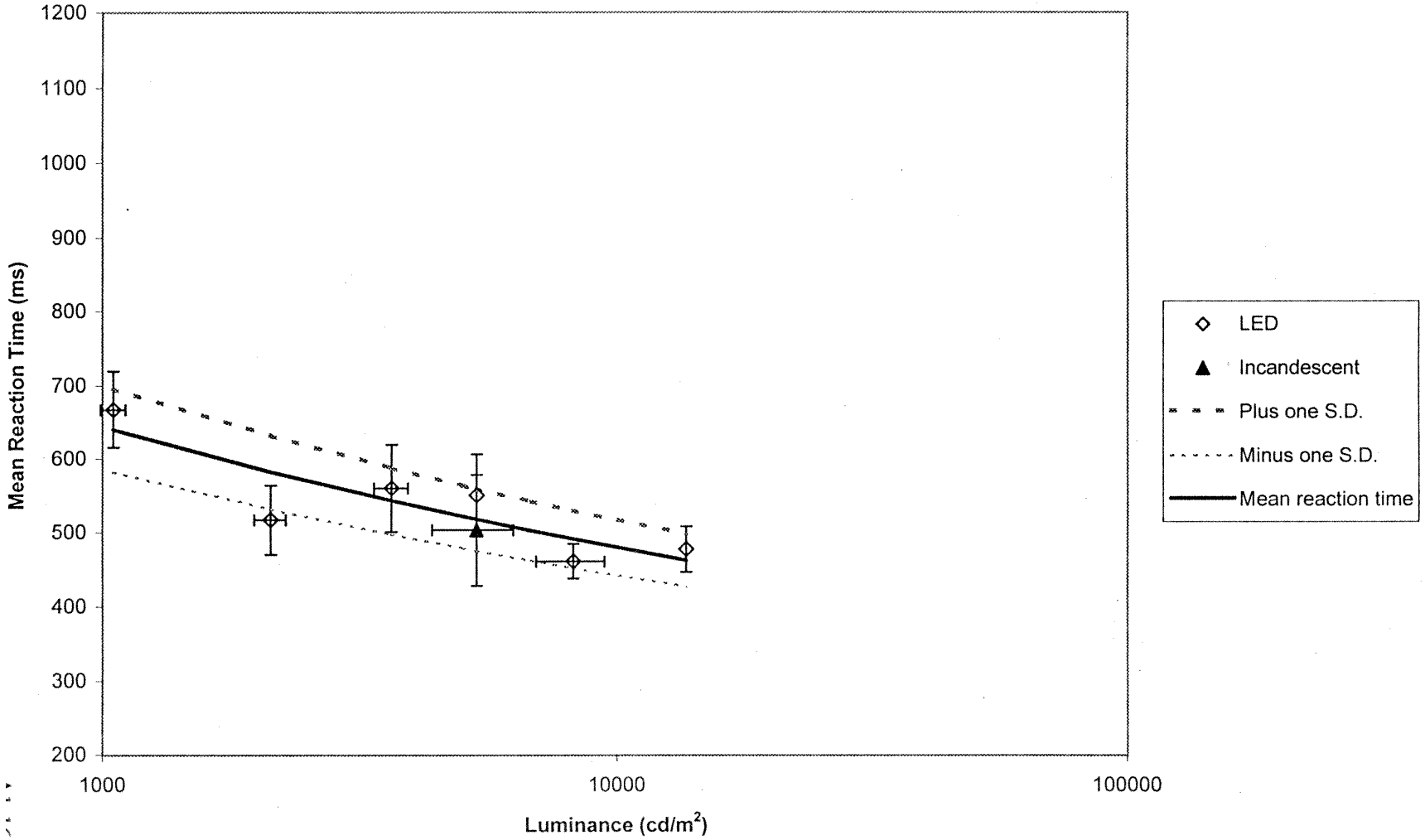
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject E, Green Signal



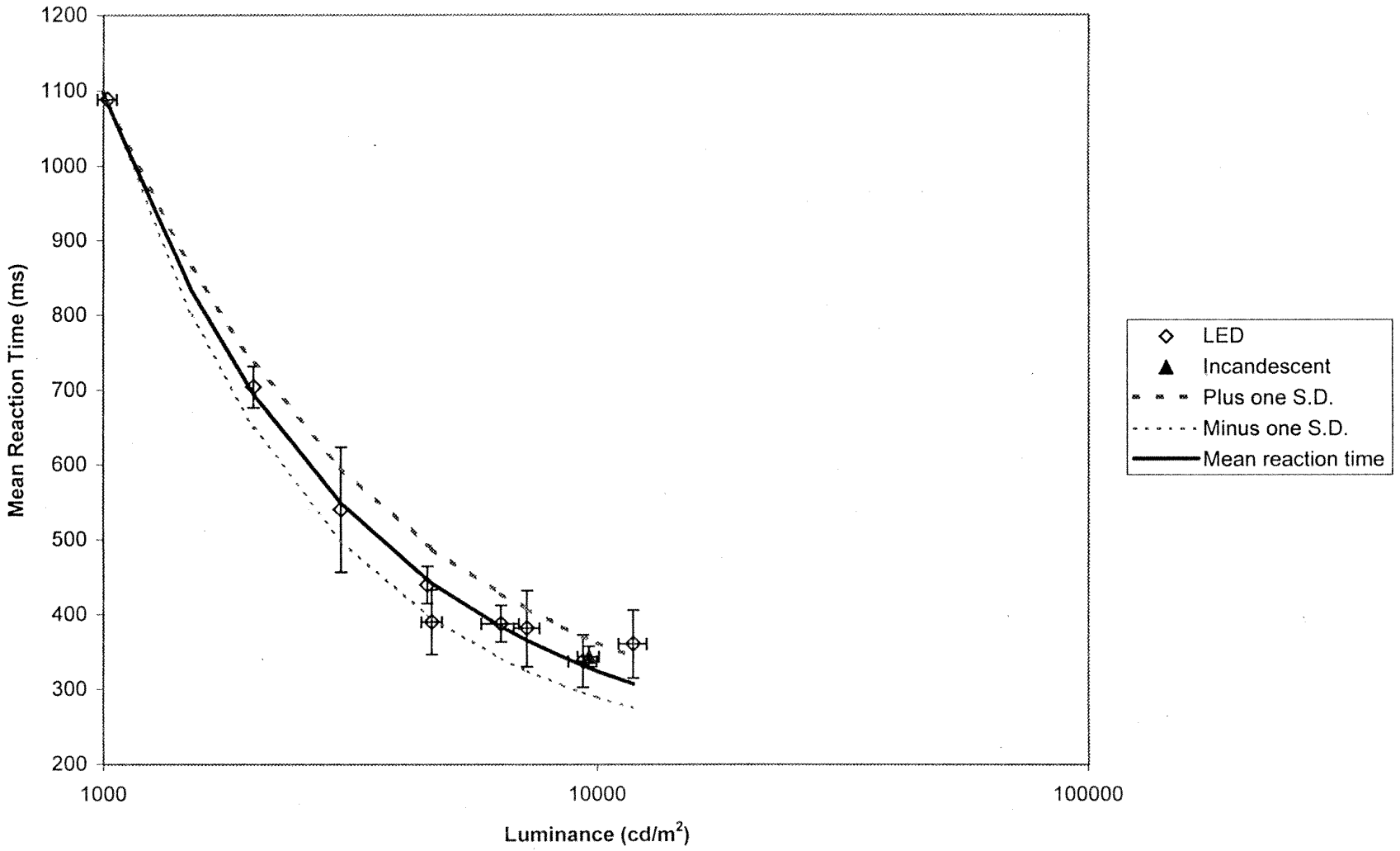
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject E, Yellow Signal



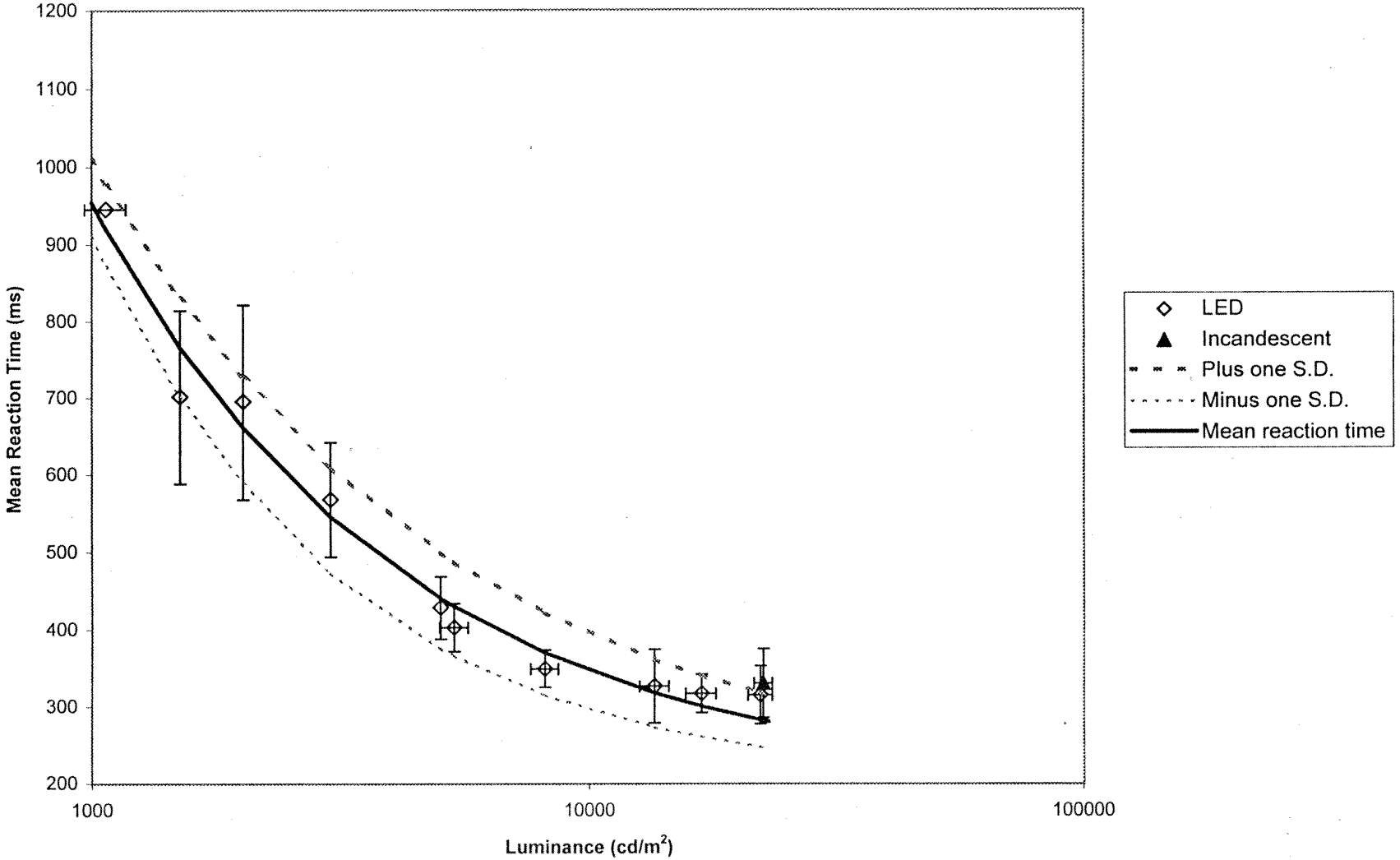
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject E, Red Signal



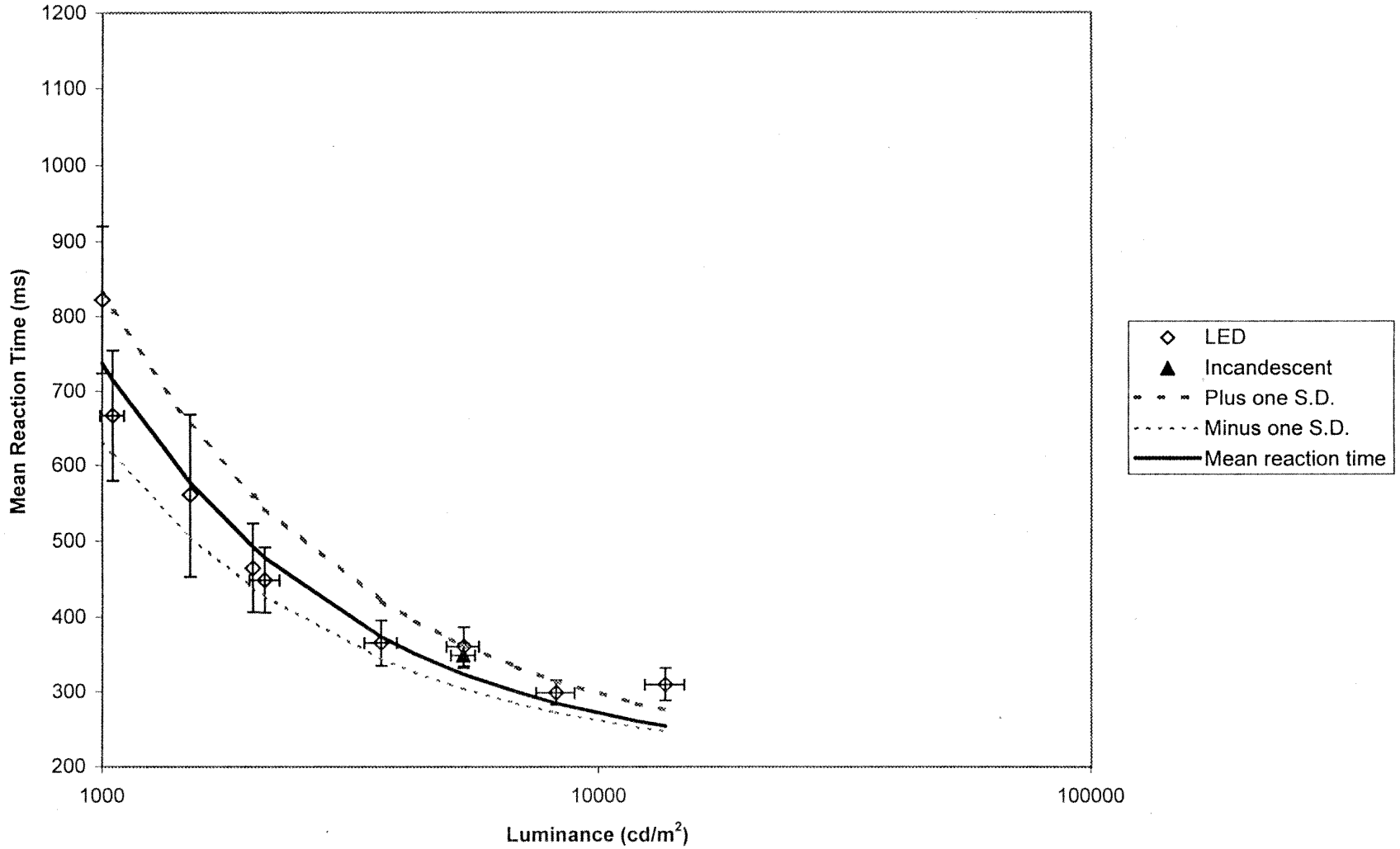
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject F, Green Signal



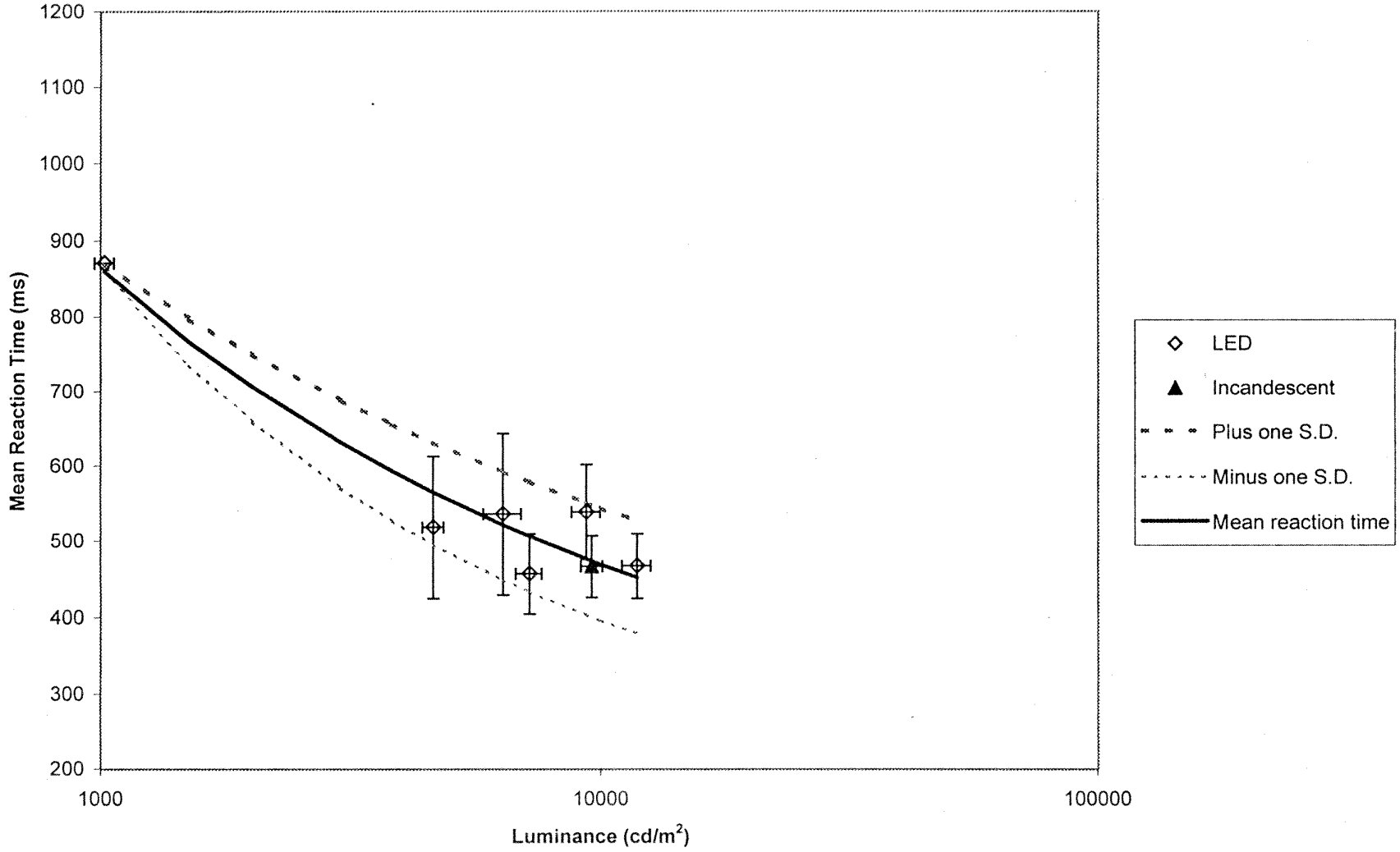
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject F, Yellow Signal



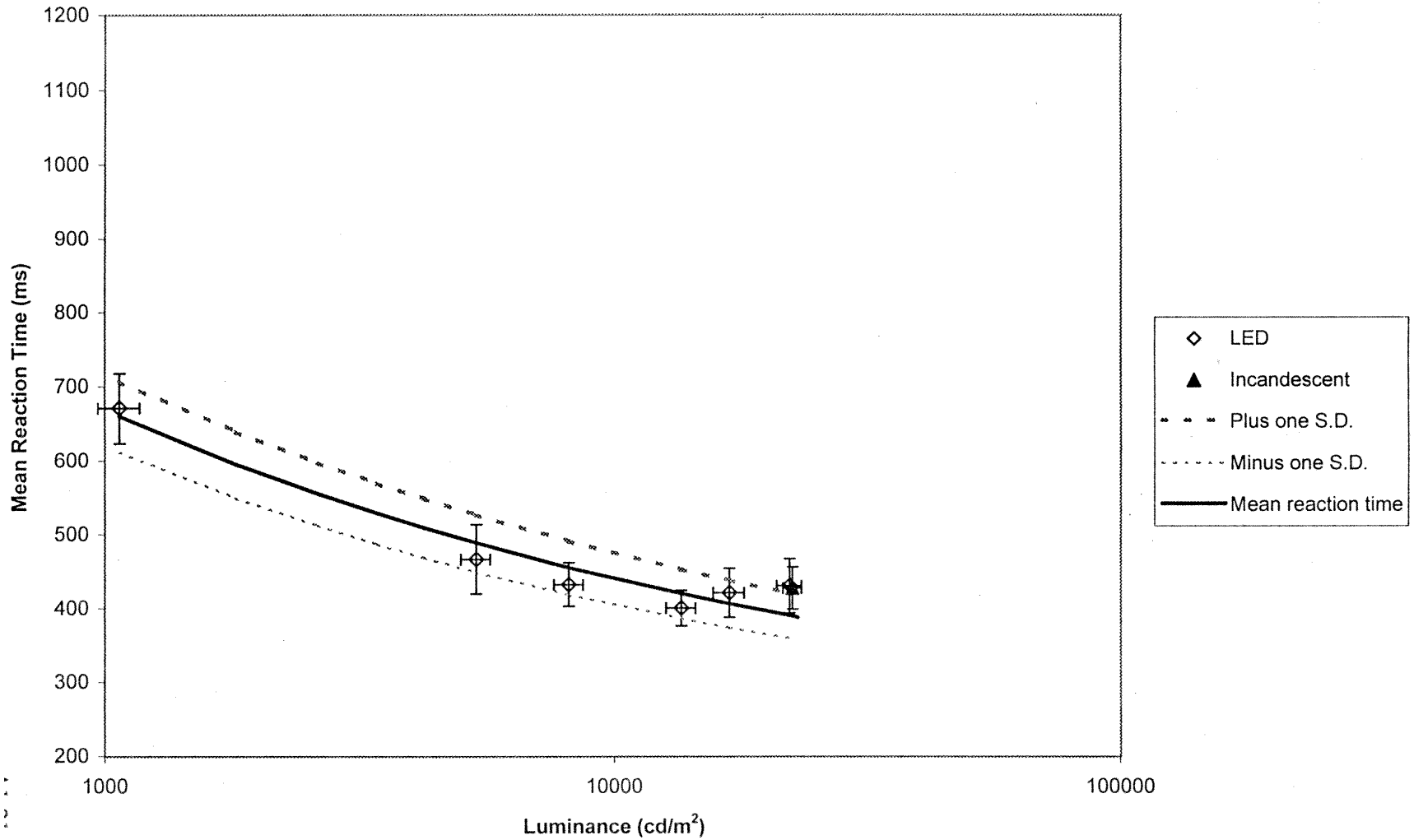
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject F, Red Signal



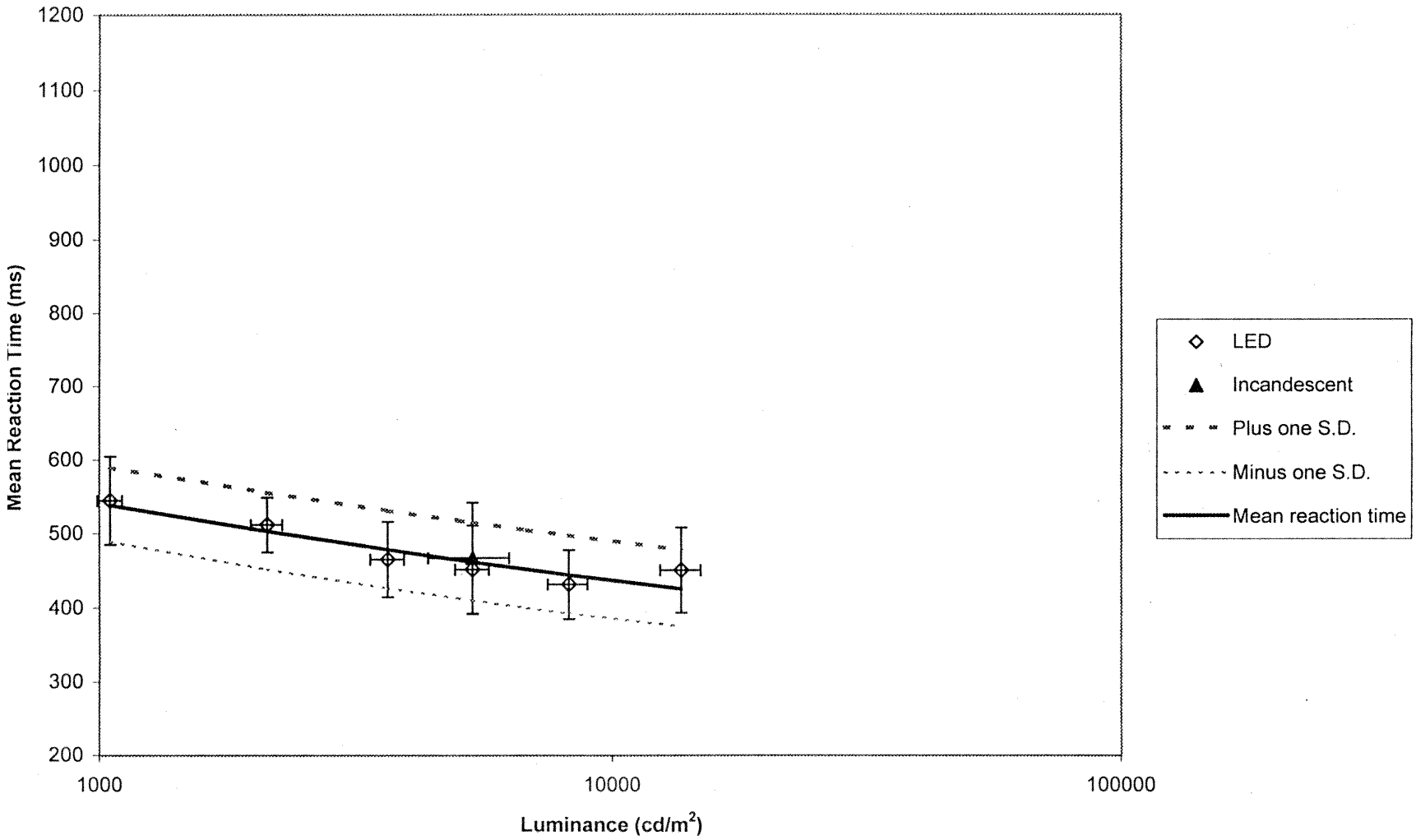
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Green Signal



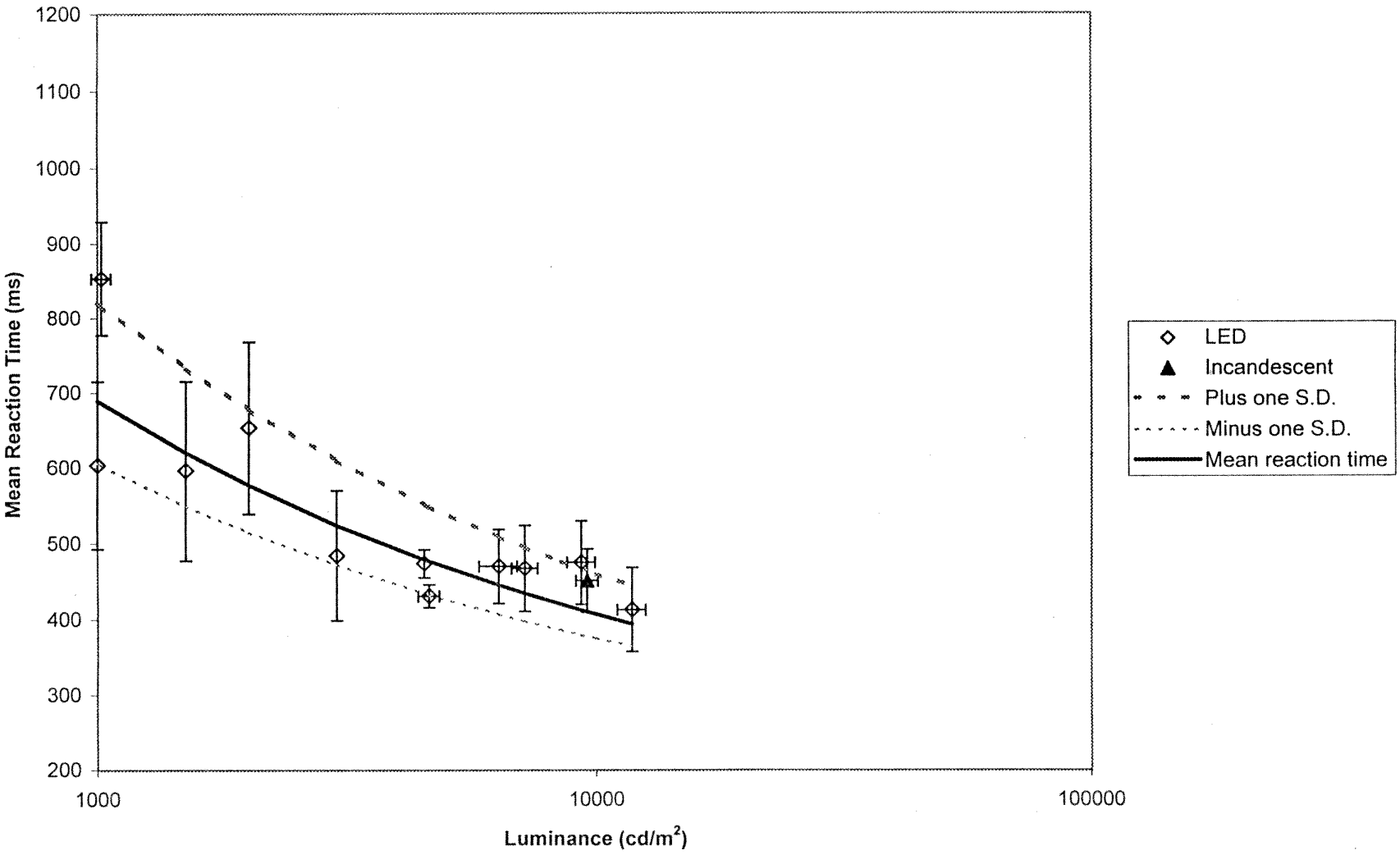
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Yellow Signal



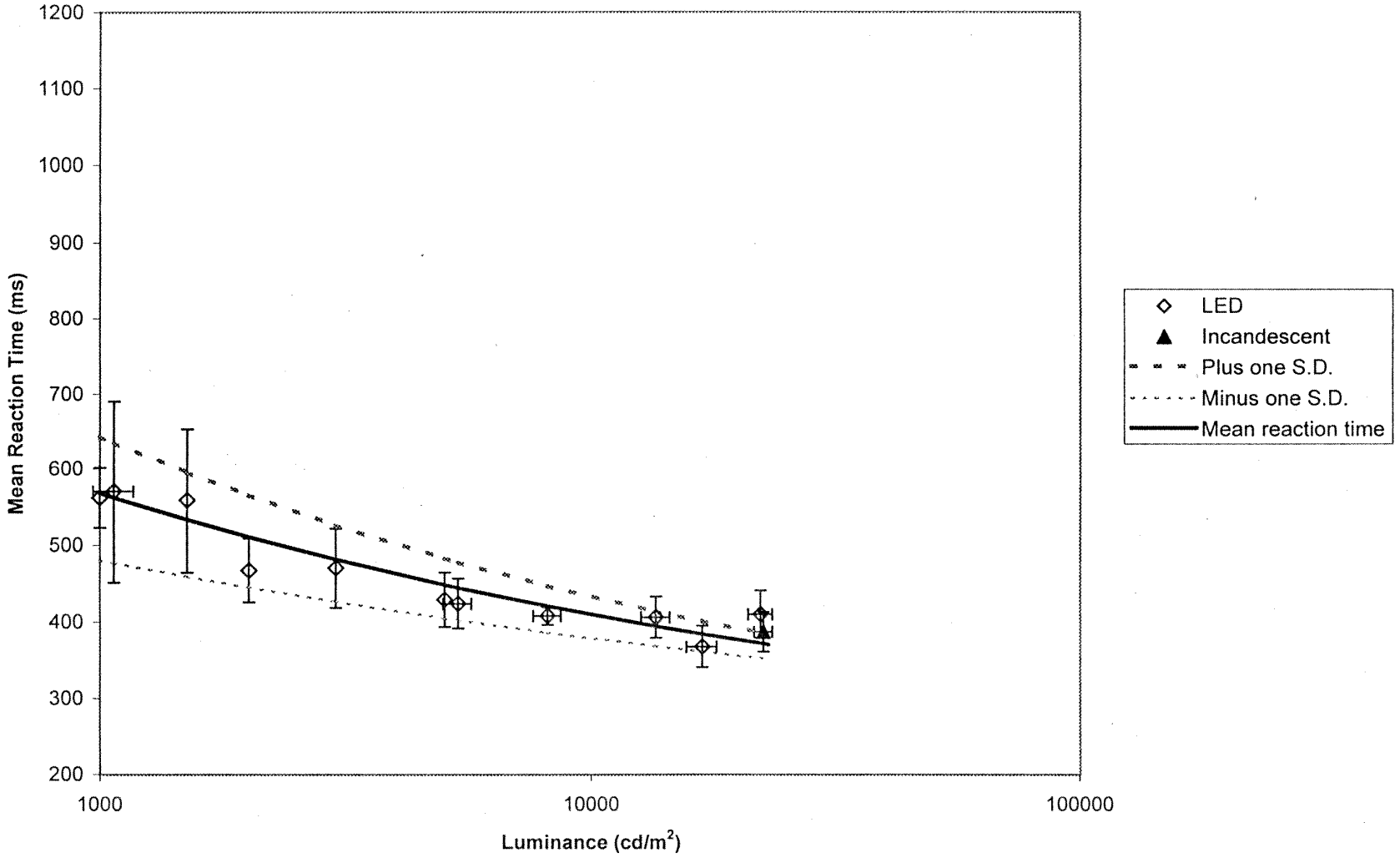
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject G, Red Signal



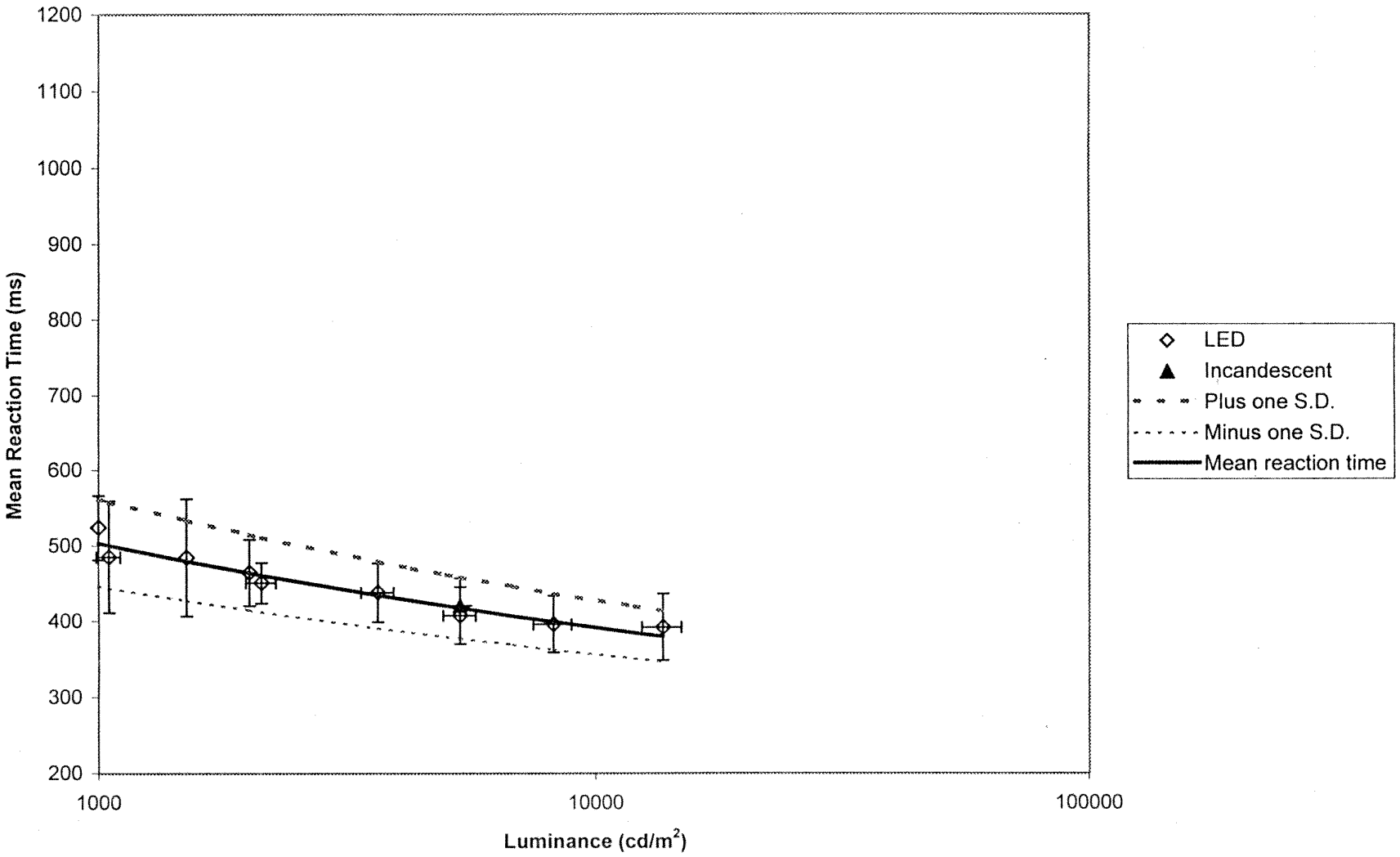
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Green Signal



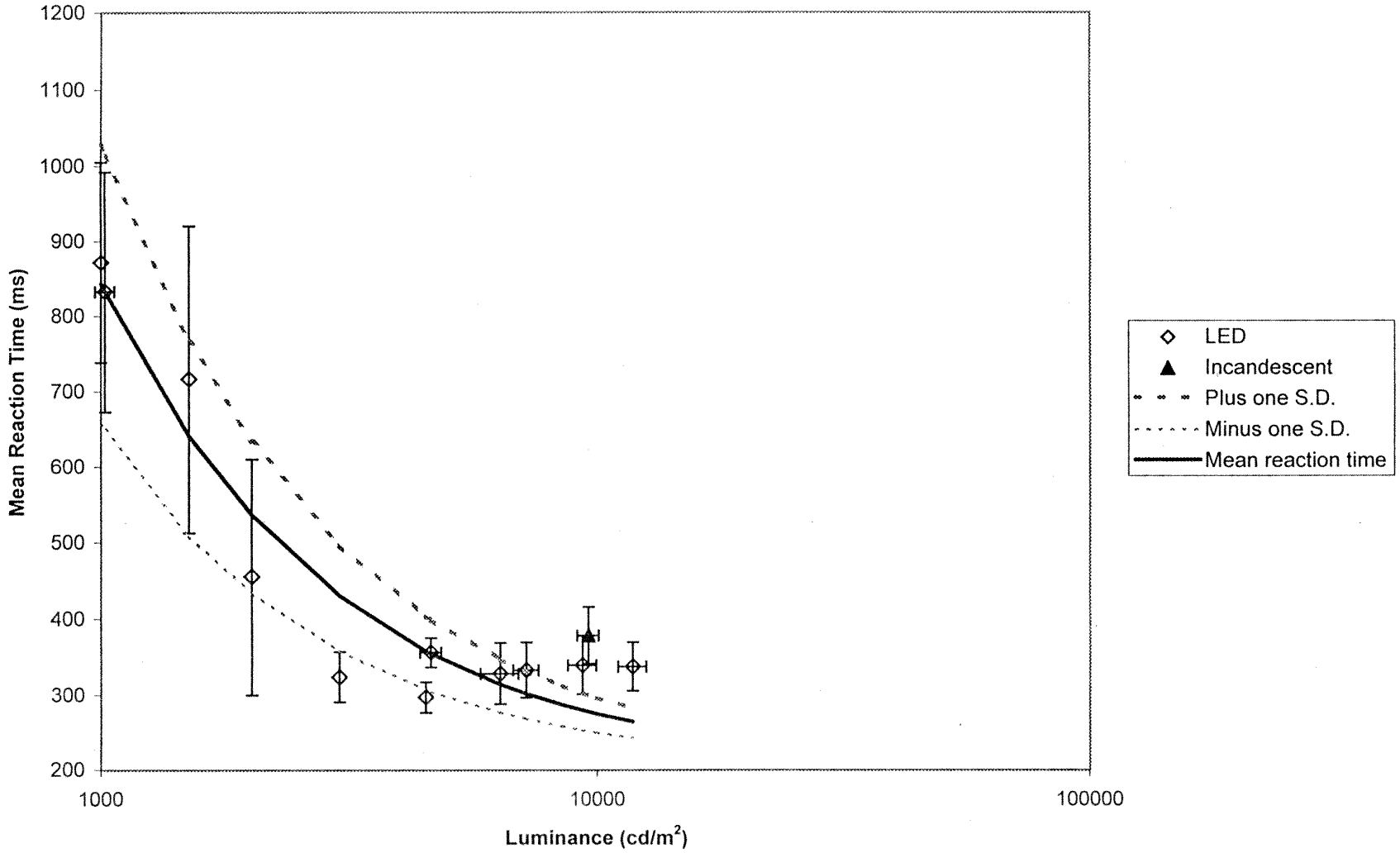
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Yellow Signal



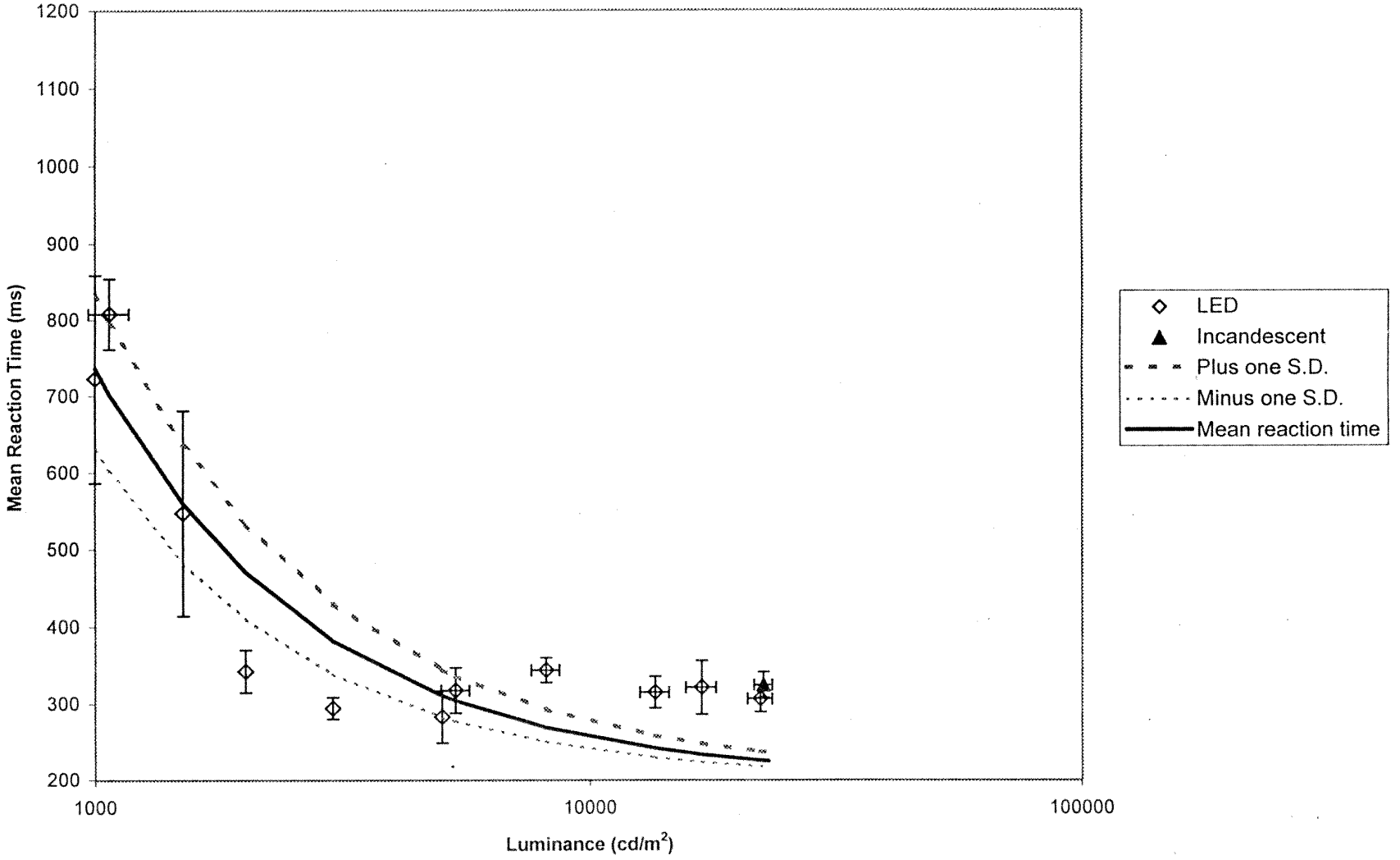
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject H, Red Signal



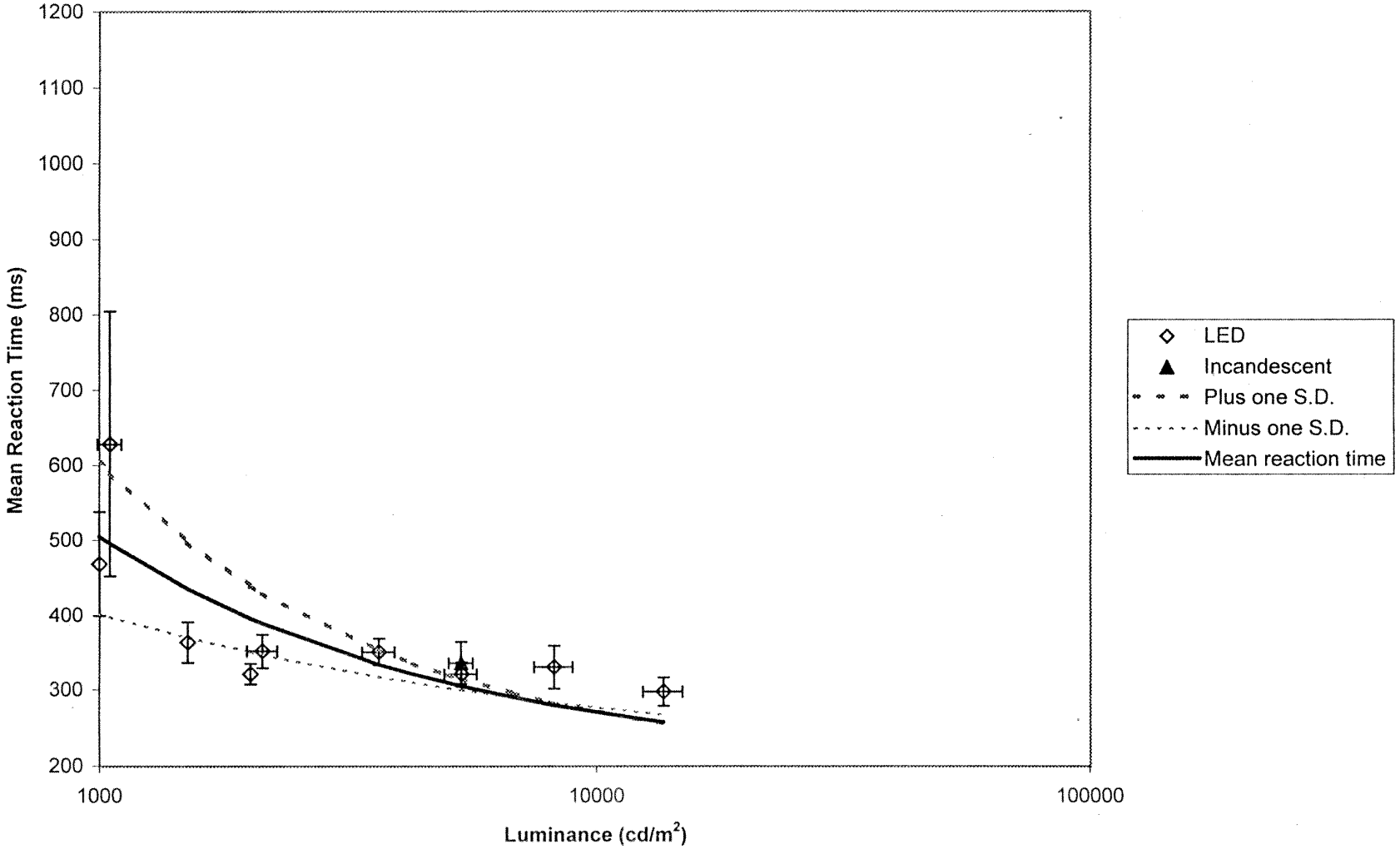
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Green Signal



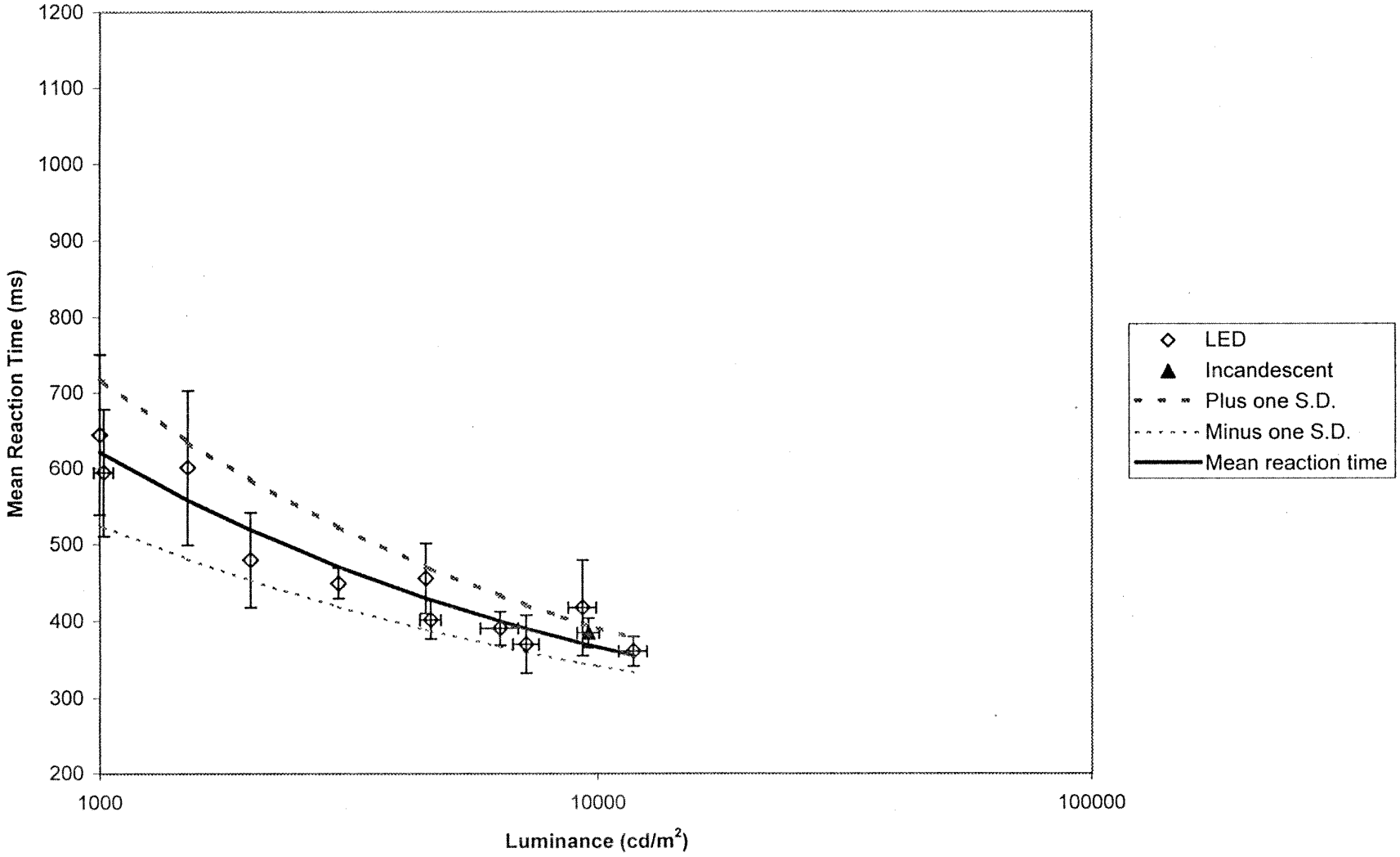
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Yellow Signal



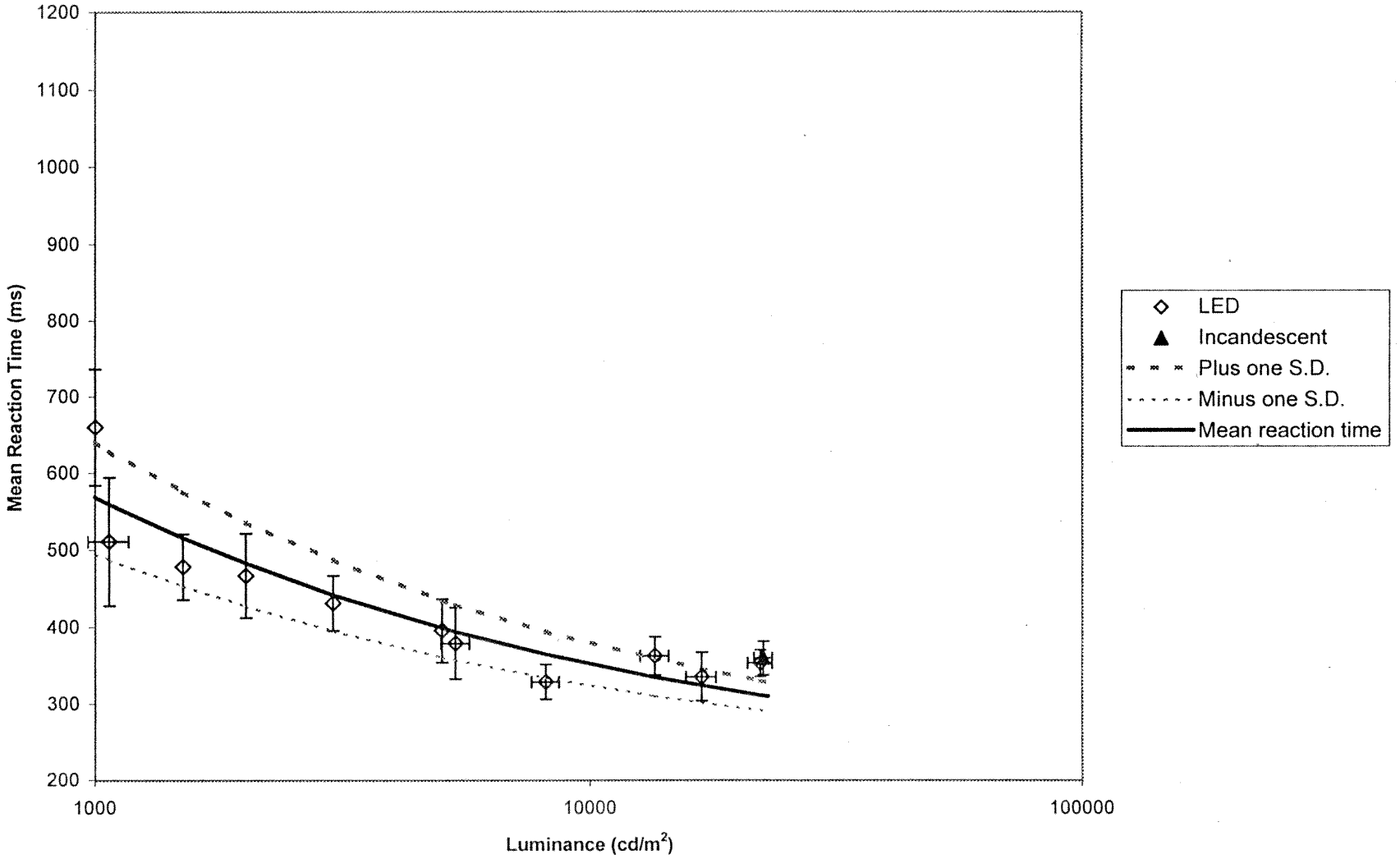
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject I, Red Signal



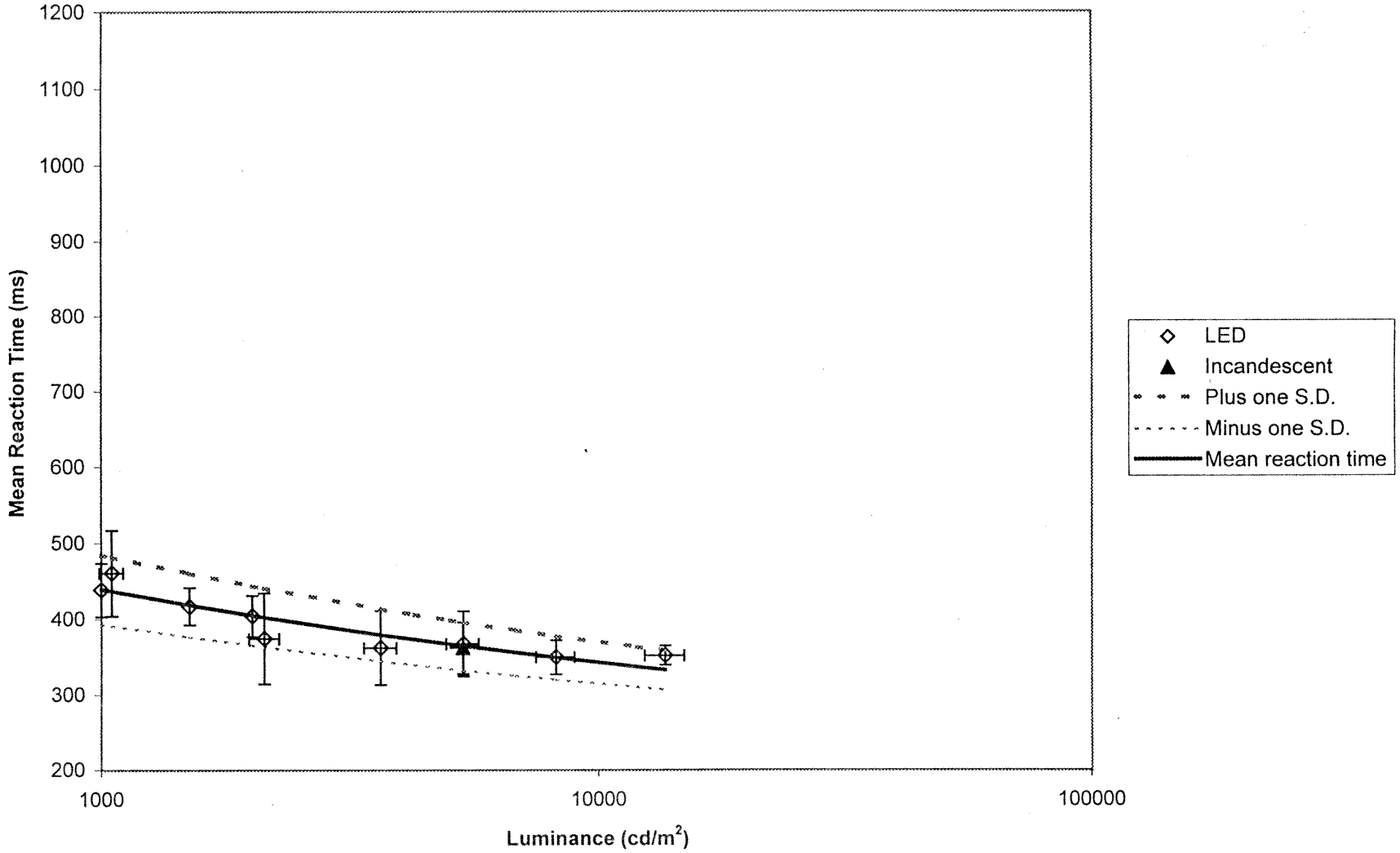
Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject J, Green Signal



Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject J, Yellow Signal



Best Fitted Curves though Mean Reaction Time, Mean Reaction Time Plus One Standard Deviation, and Mean Reaction Time Minus One Standard Deviation For Subject J, Red Signal

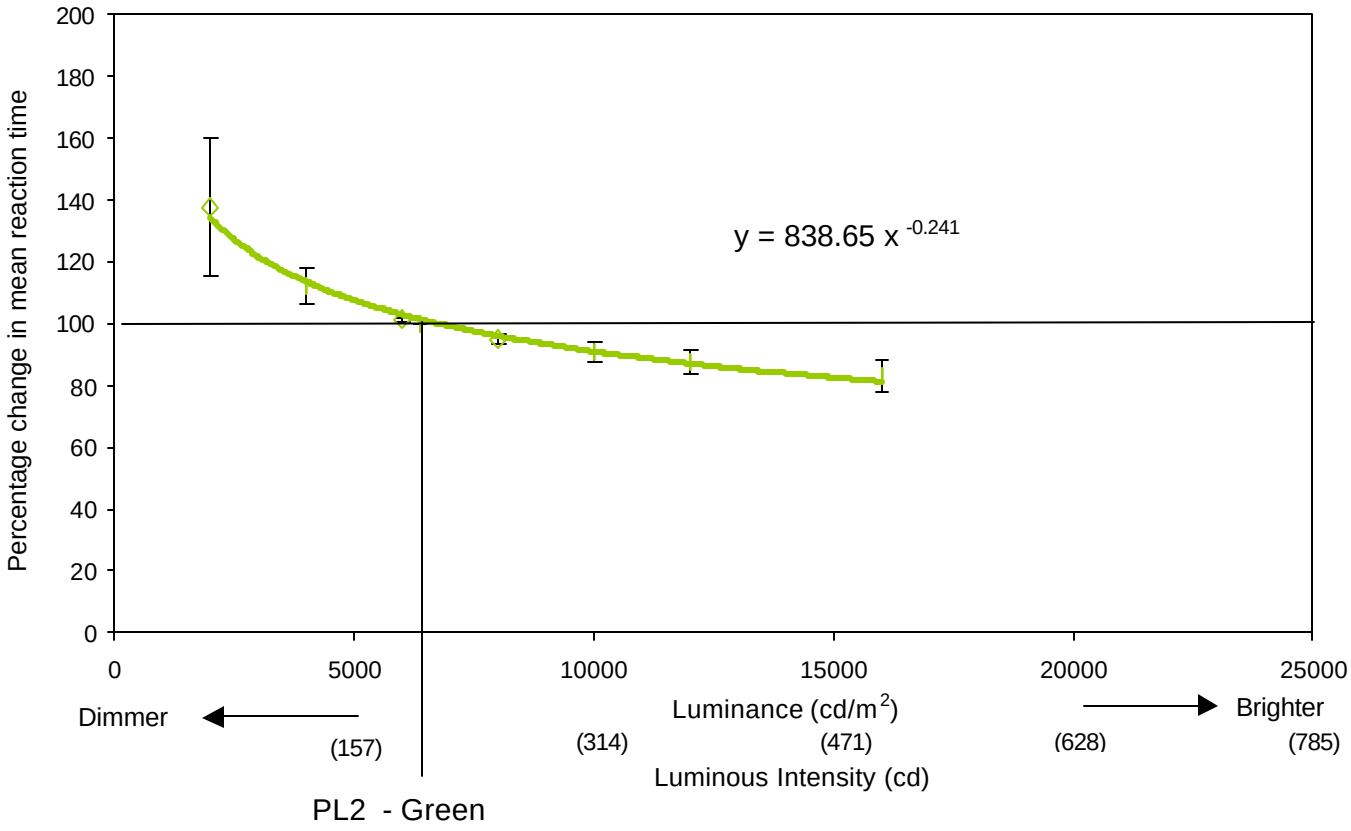


Appendix 2

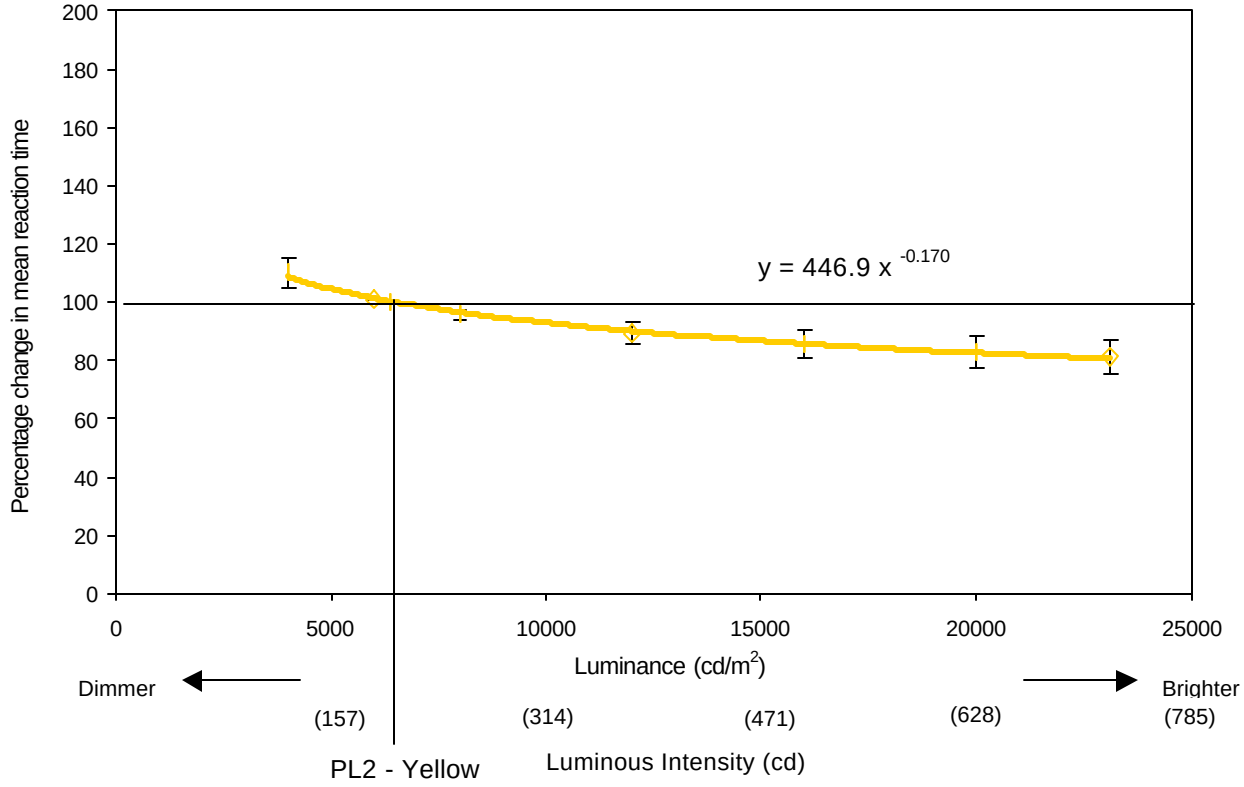
Percentage Change in Reaction Time Normalized to Performance Level 2 of the Draft European Standard for a 200 mm Diameter Signal

The following three figures show the percentage change in mean reaction time for the red, yellow and green LED signals calculated from the best fitting curves through the mean reaction times for each individual subject (see Appendix 1 for the curves). For the red, yellow and green LED signals, 100% reaction time is at a luminance of 6366 cd/m^2.

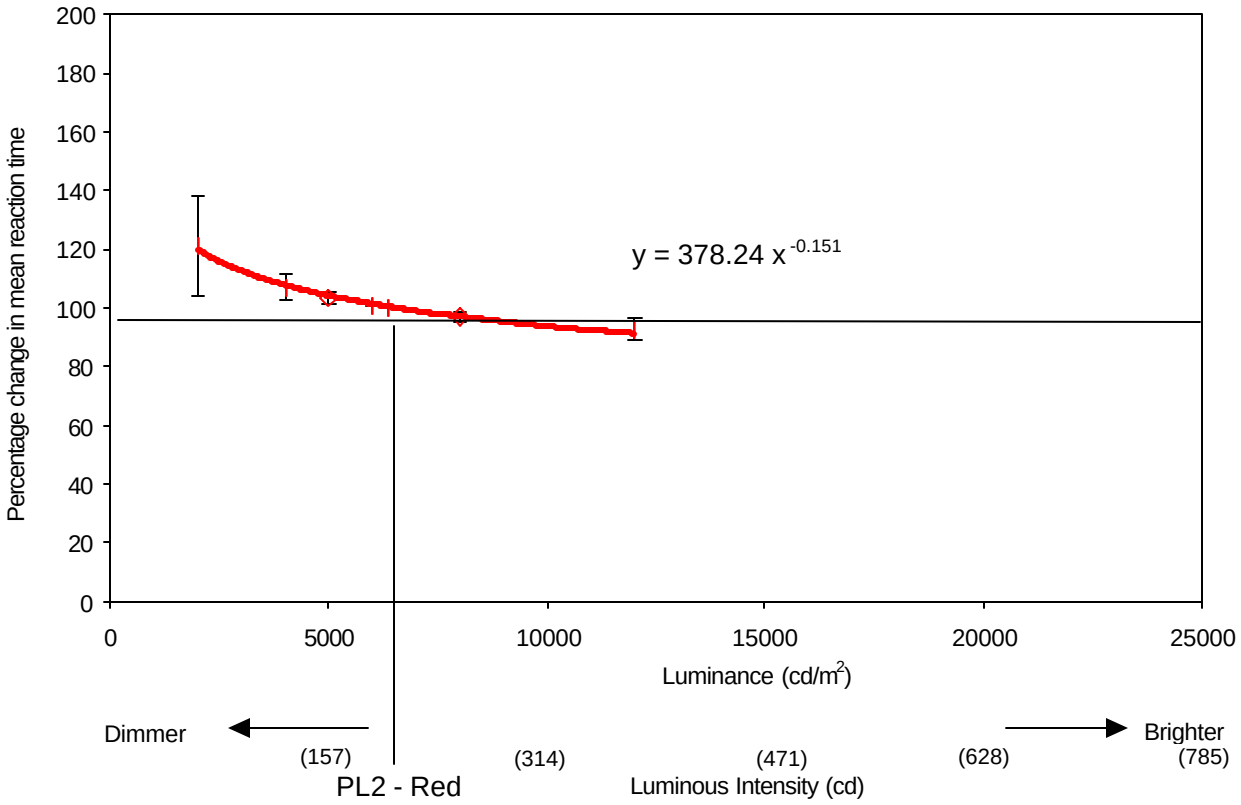
Percentage Reaction Time Change for Green Signal:
PL2 Standard.



Percentage Reaction Time Change for Yellow Signal:
PL2 Standard



Percentage Reaction Time Change for Red Signal:
PL2 Standard

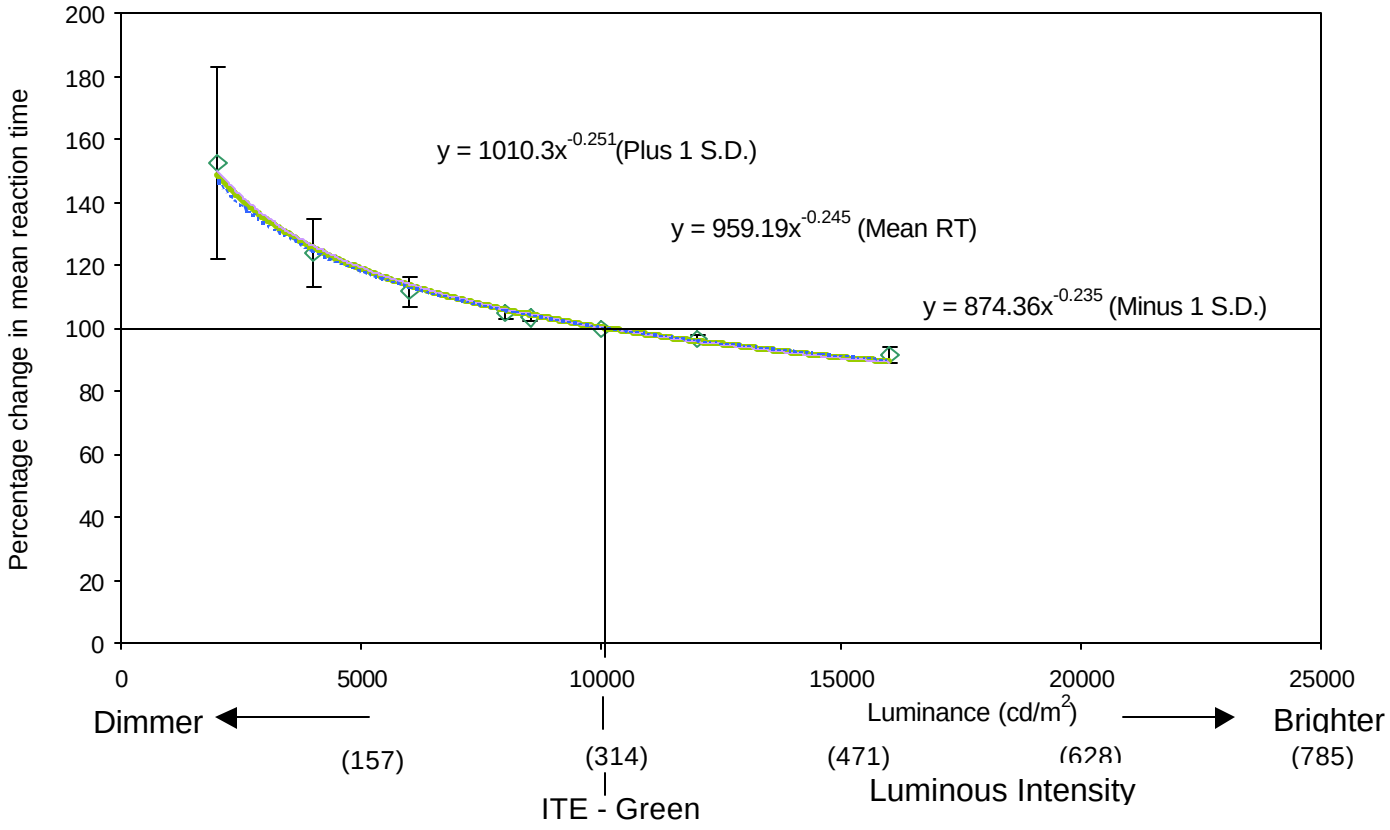


Appendix 3

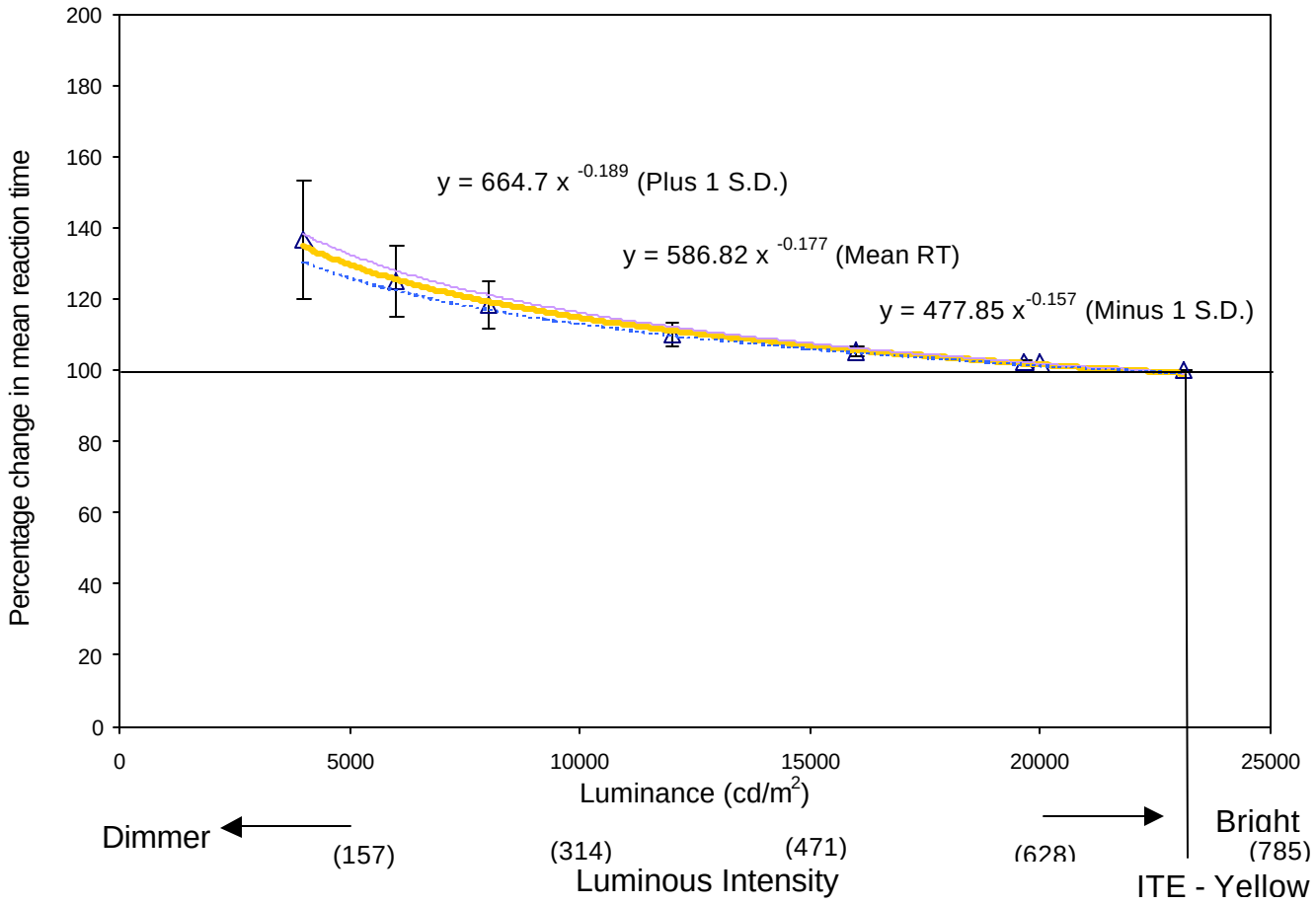
Percentage Change in Reaction Time Based on Different Individual Curves

The following three figures show the percentage change in mean reaction time for the red, yellow and green LED signals calculated from the best fitting curves through the mean reaction times, the mean reaction times plus one standard deviation and the mean reaction times minus one standard deviation for each individual subject (see Appendix 1 for the curves). For the red LED signal, 100% reaction time is at a luminance of 5000 cd/m^2. For the yellow LED signal, 100% reaction time is at a luminance of 23,121 cd/m^2. For the green LED signal, 100% reaction time is at a luminance of 10,000 cd/m^2. The fact that the percentage changes are very similar for all three curves, for the same signal color, indicates the predictive equations for percentage change in reaction time are robust.

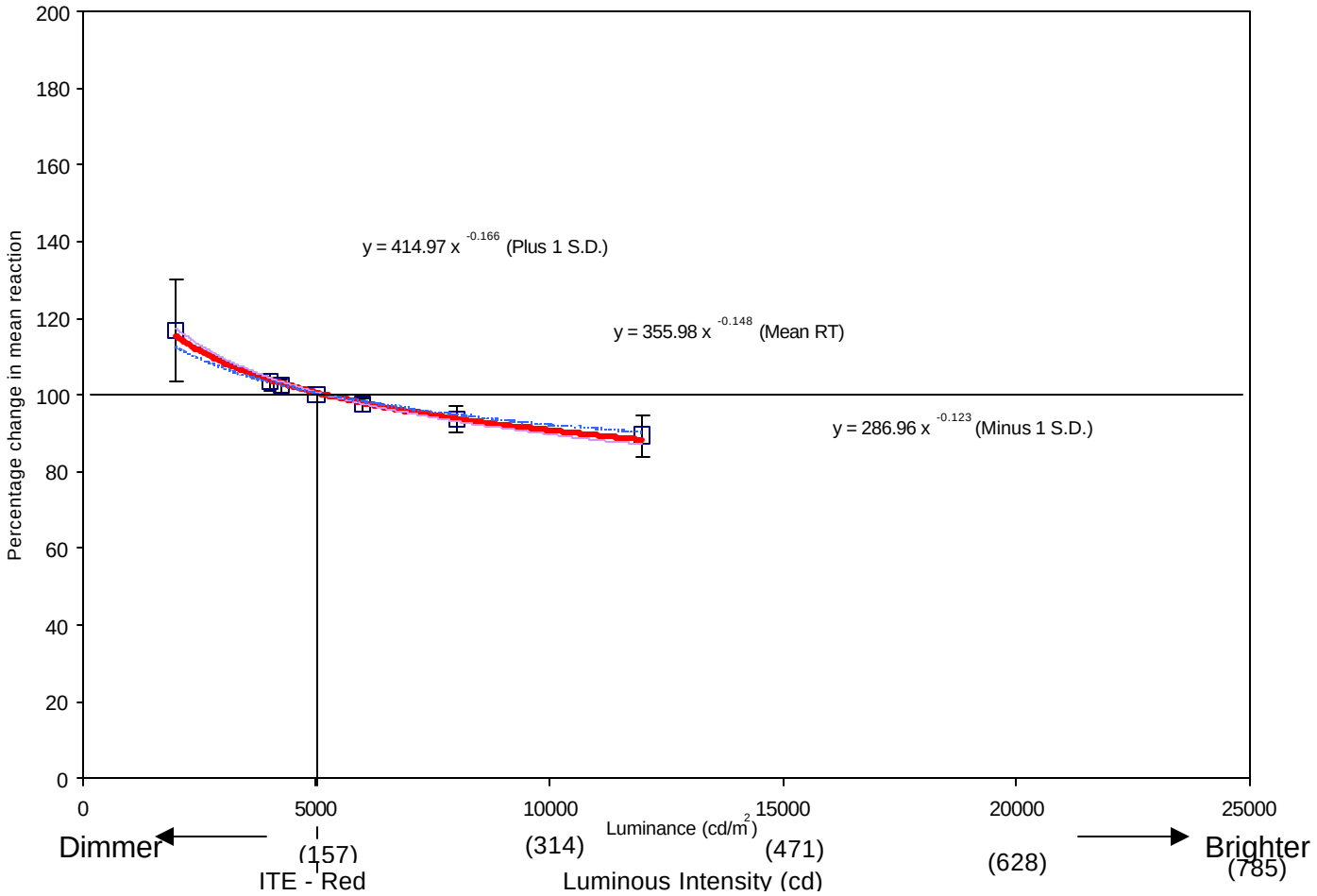
Percentage Reaction Time Change for Green Signal:
ITE Standard



Percentage Reaction Time Change for Yellow Signal:
ITE Standard



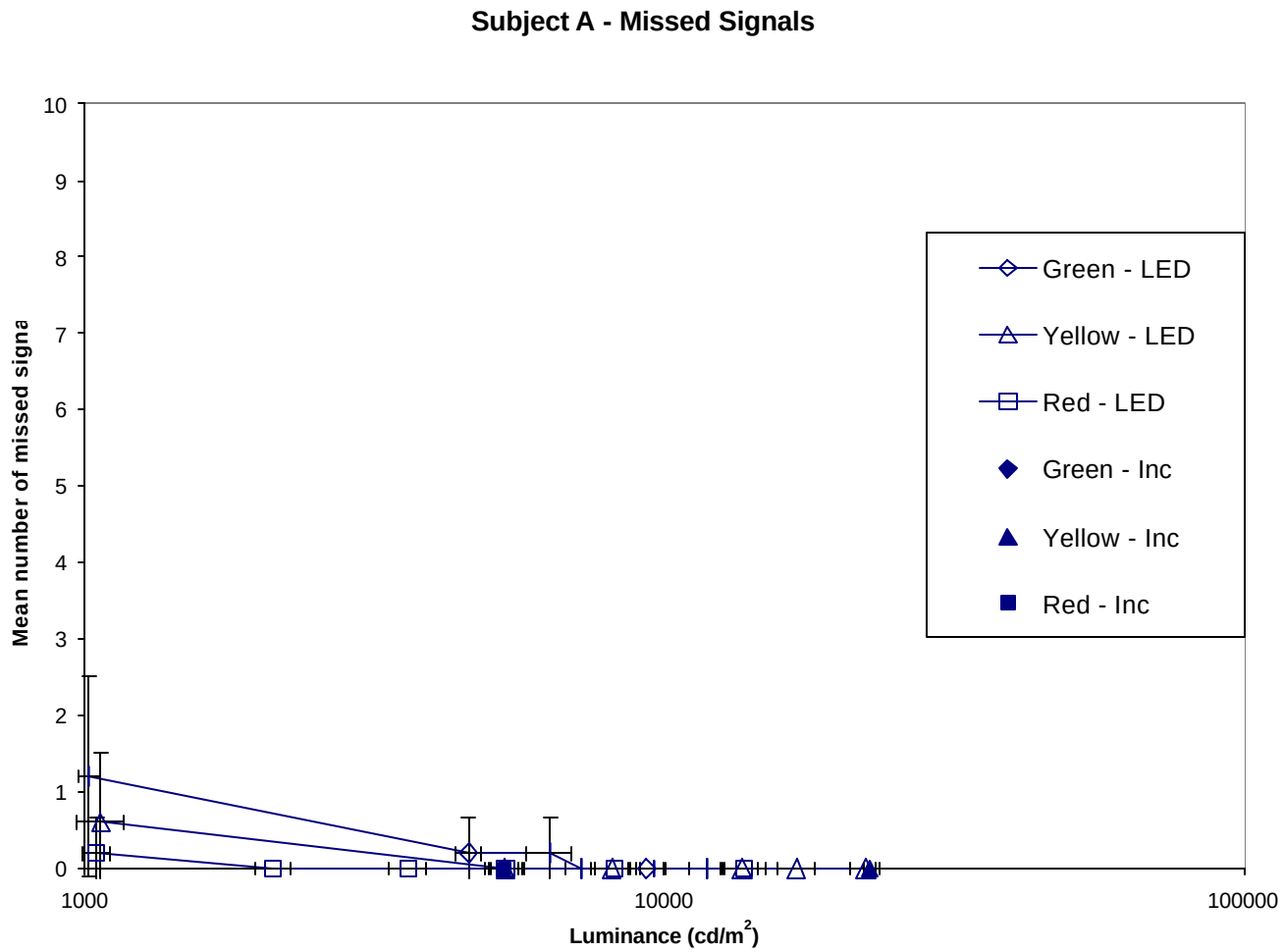
Percentage Reaction Time Change for Red Signal: ITE Standard

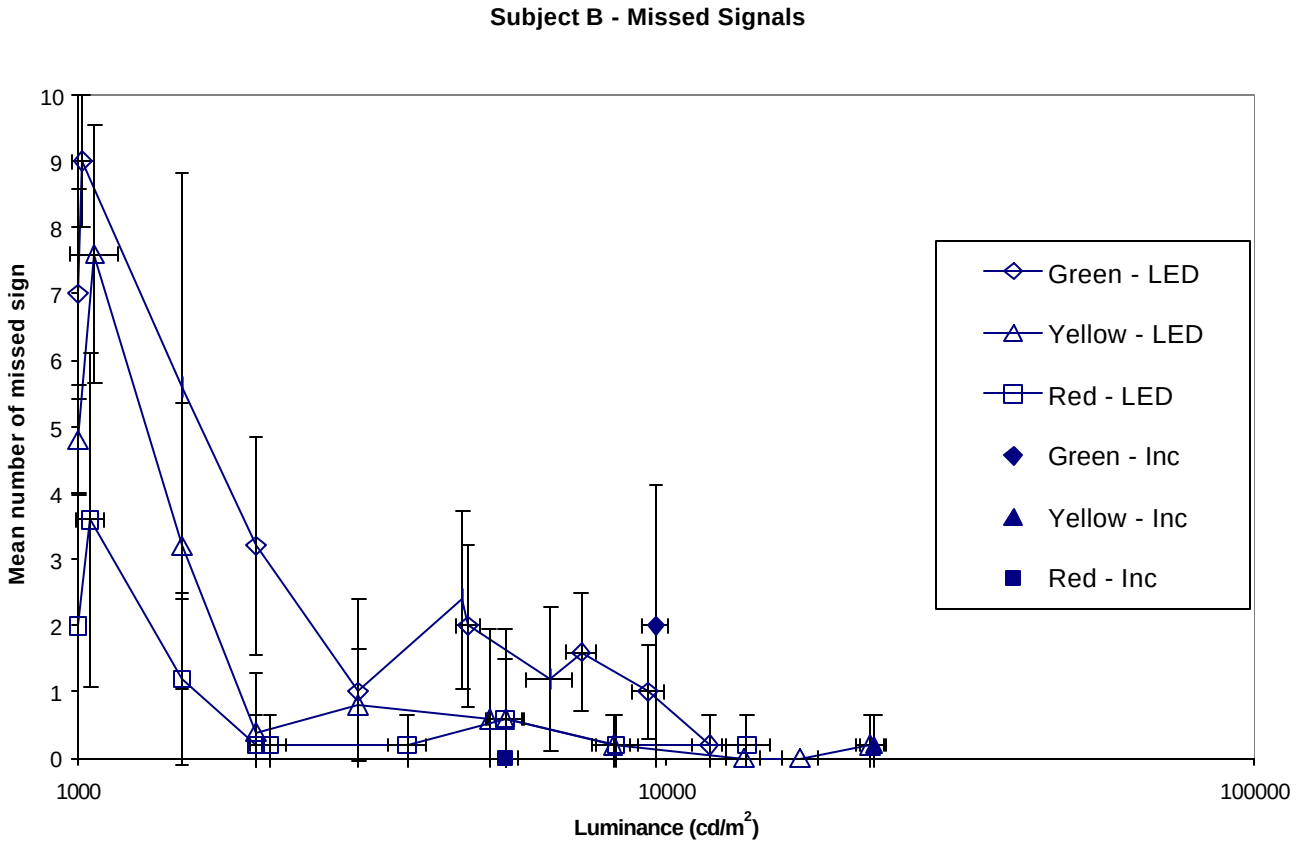


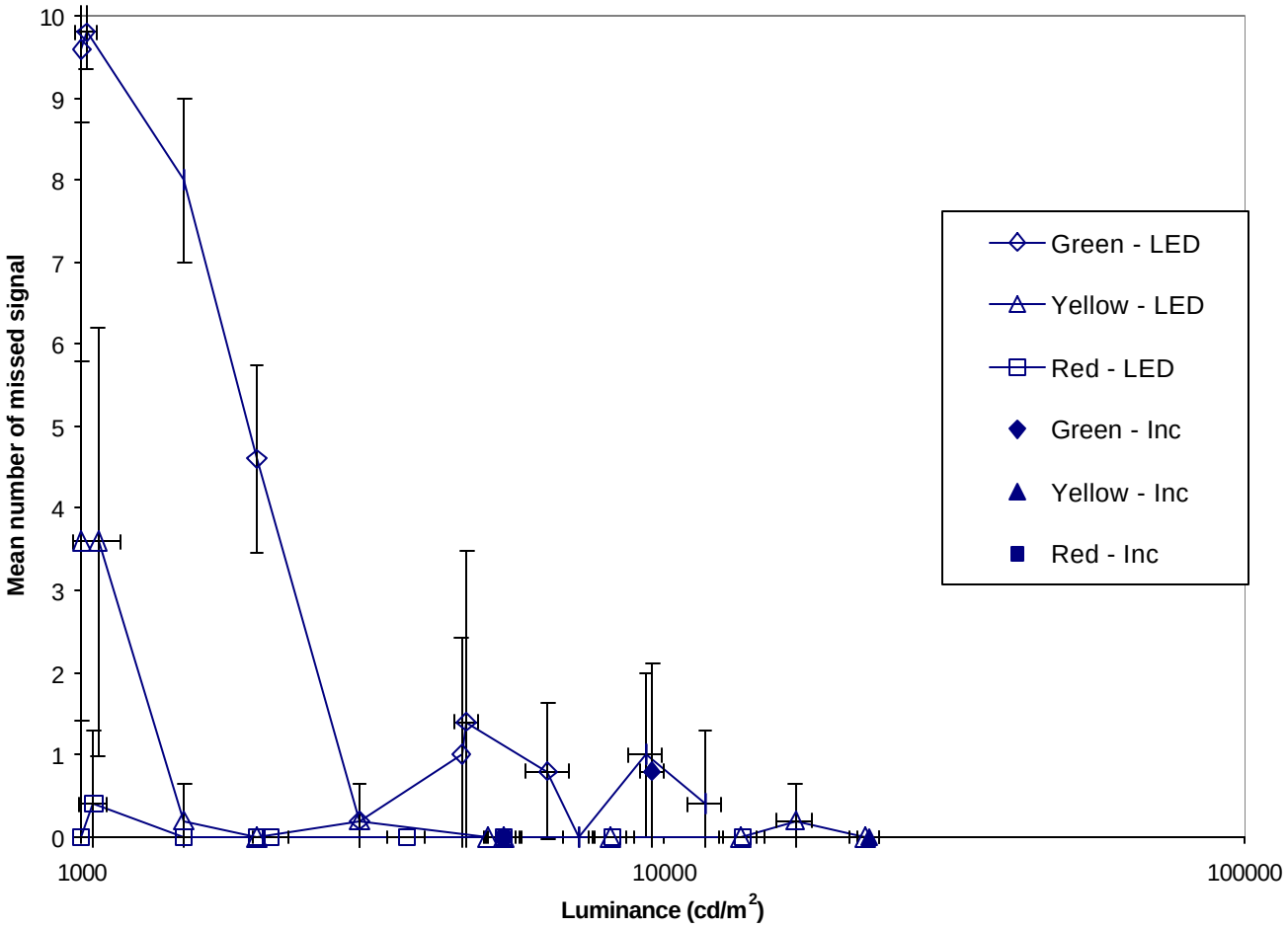
Appendix 4

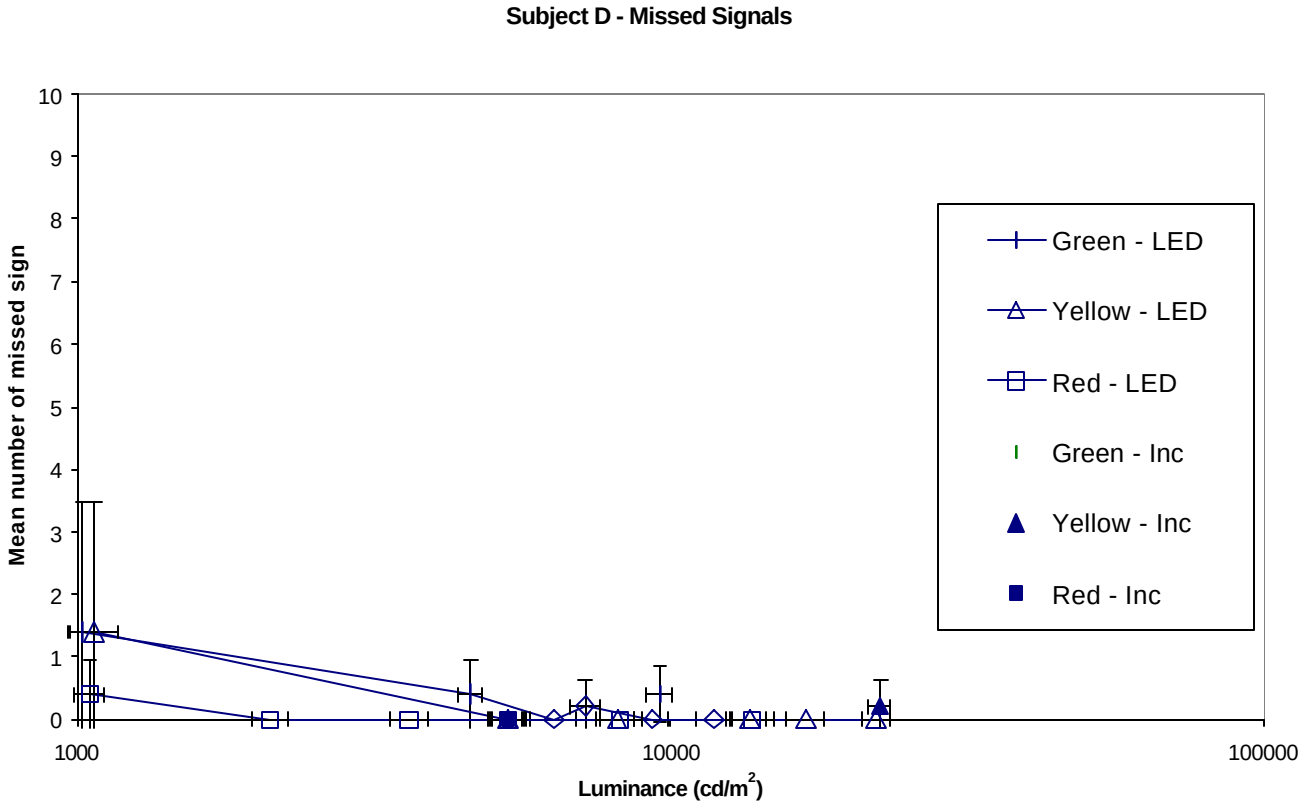
Missed Signals for Individual Subjects

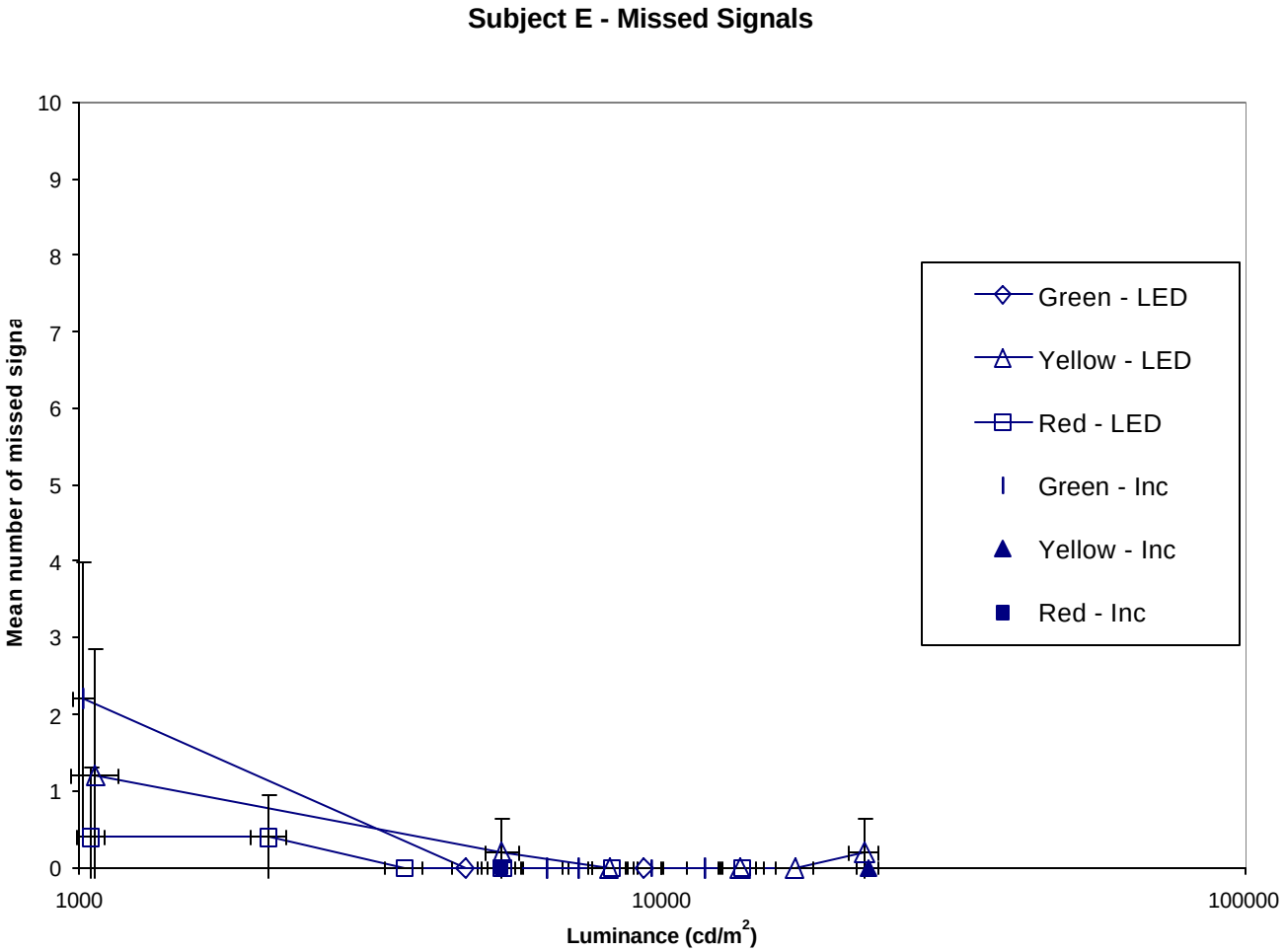
The following figures show the mean number of signals missed plotted against the signal luminance, for each subject when viewing each combination of luminance and color used in the first and third experiments. The y-axis error bars correspond to one standard deviation about the mean number of signals missed. The x-axis error bars correspond to one standard deviation about the mean measured luminance. The x-axis error bars are only given for the measurements made in the first experiment. This is because for that study the luminance of the signals was measured in several different ways and the results averaged. No additional luminance measurements were made in the third experiment, the relationship between mean measured luminance and current through the LED established in the first experiment being used to predict the current required to achieve the desired signal luminance in this study.

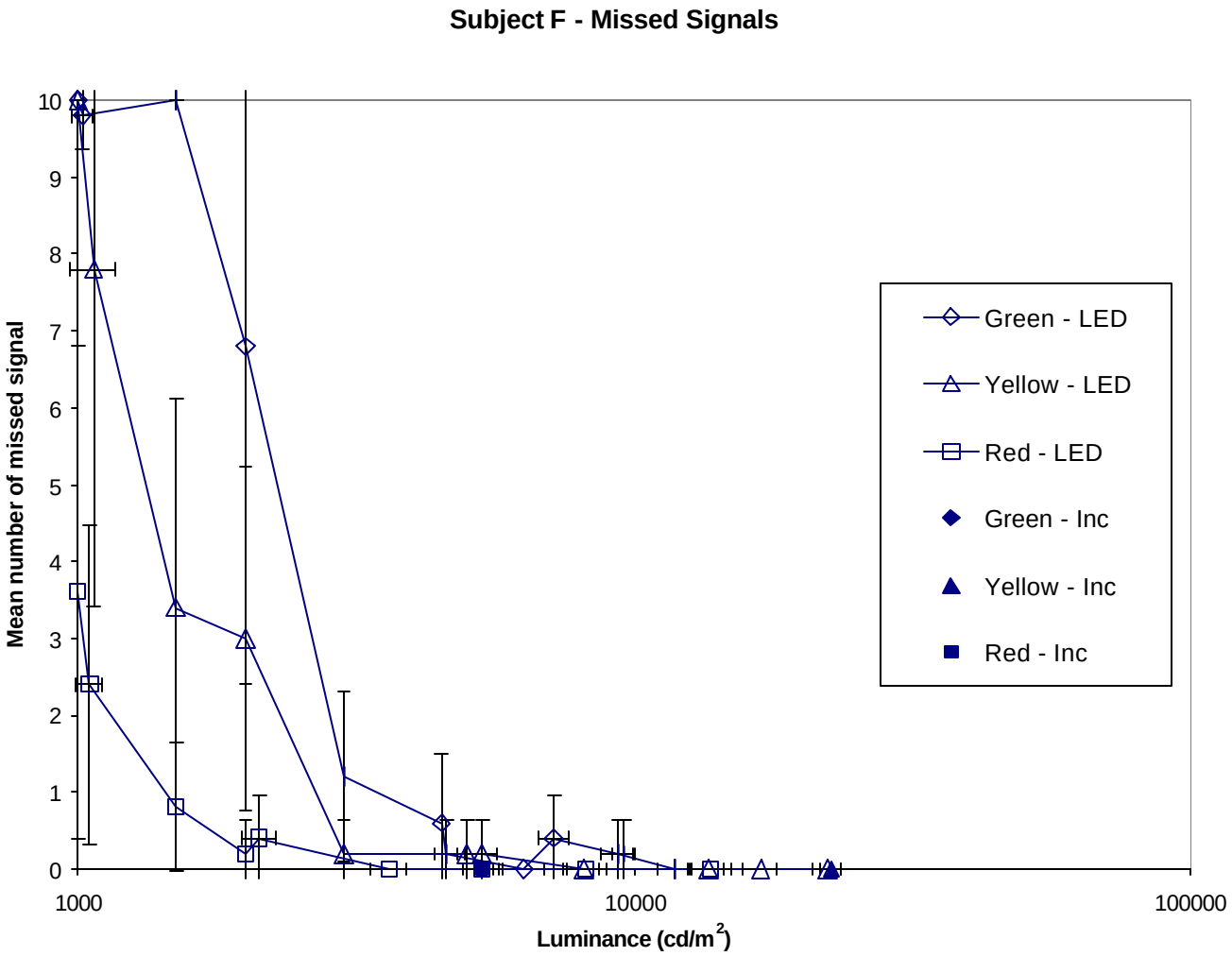

Subject A - Missed Signals
Mean number of missed signa
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc

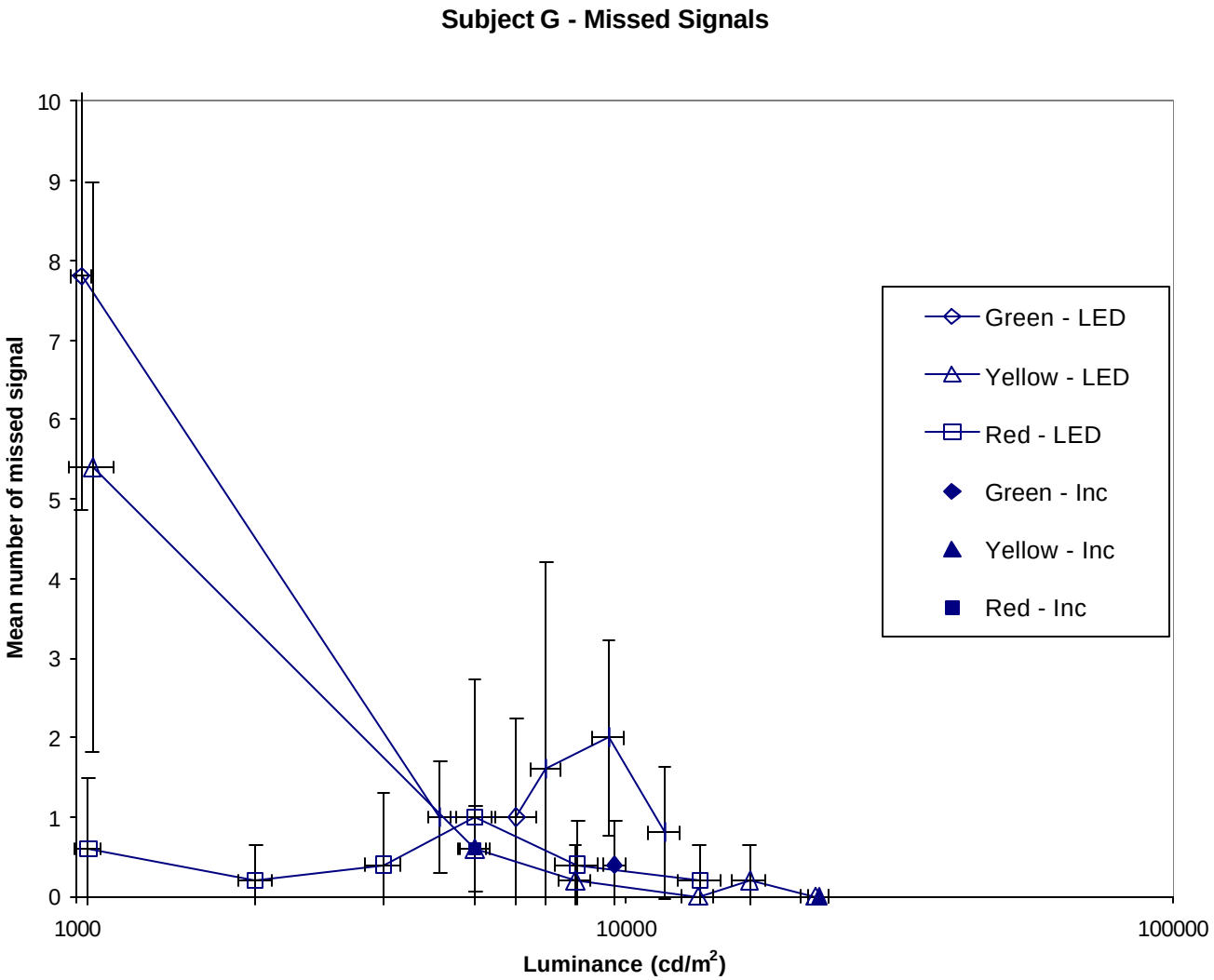

Subject B - Missed Signals
Mean number of missed sign
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc

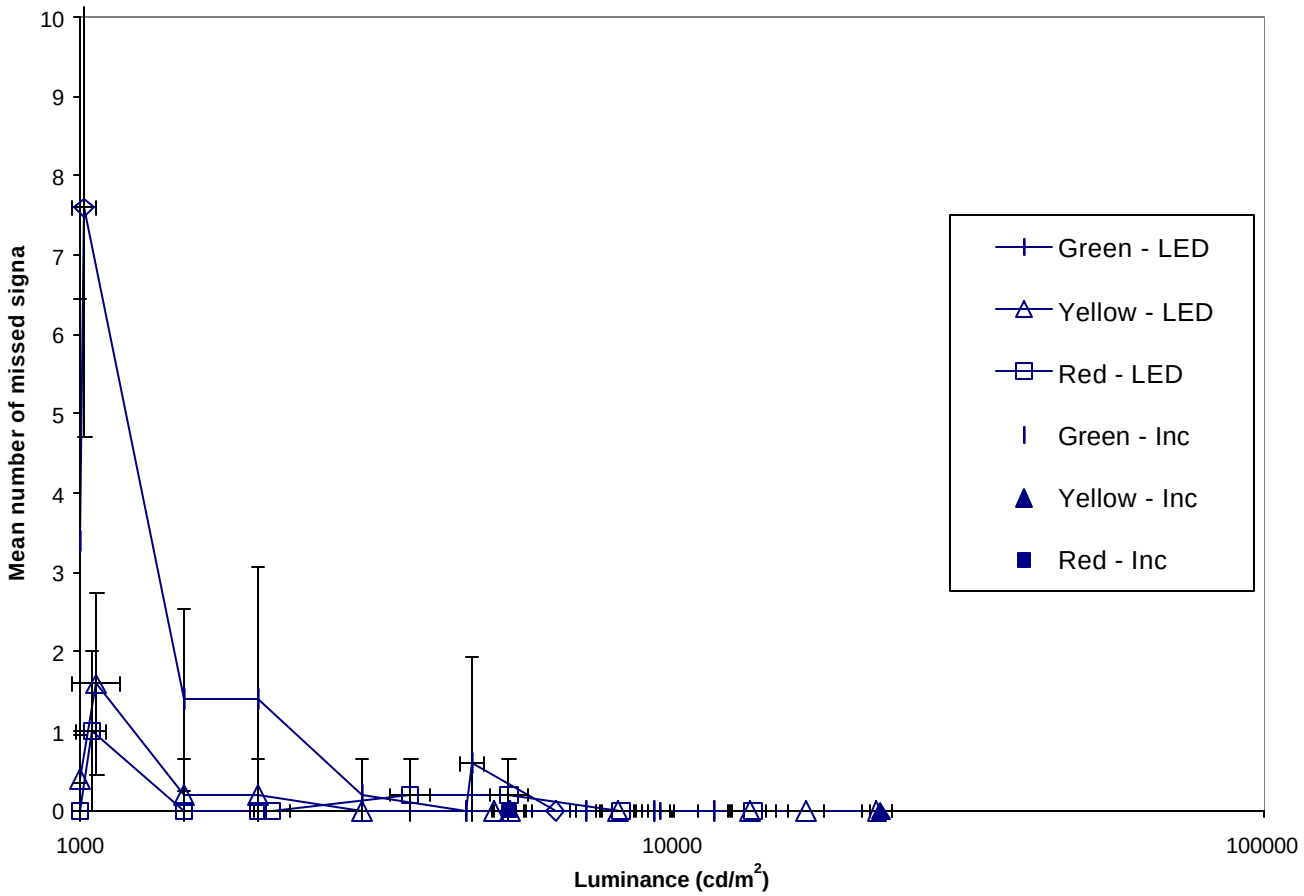

Subject C - Missed Signals
Mean number of missed signal
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc

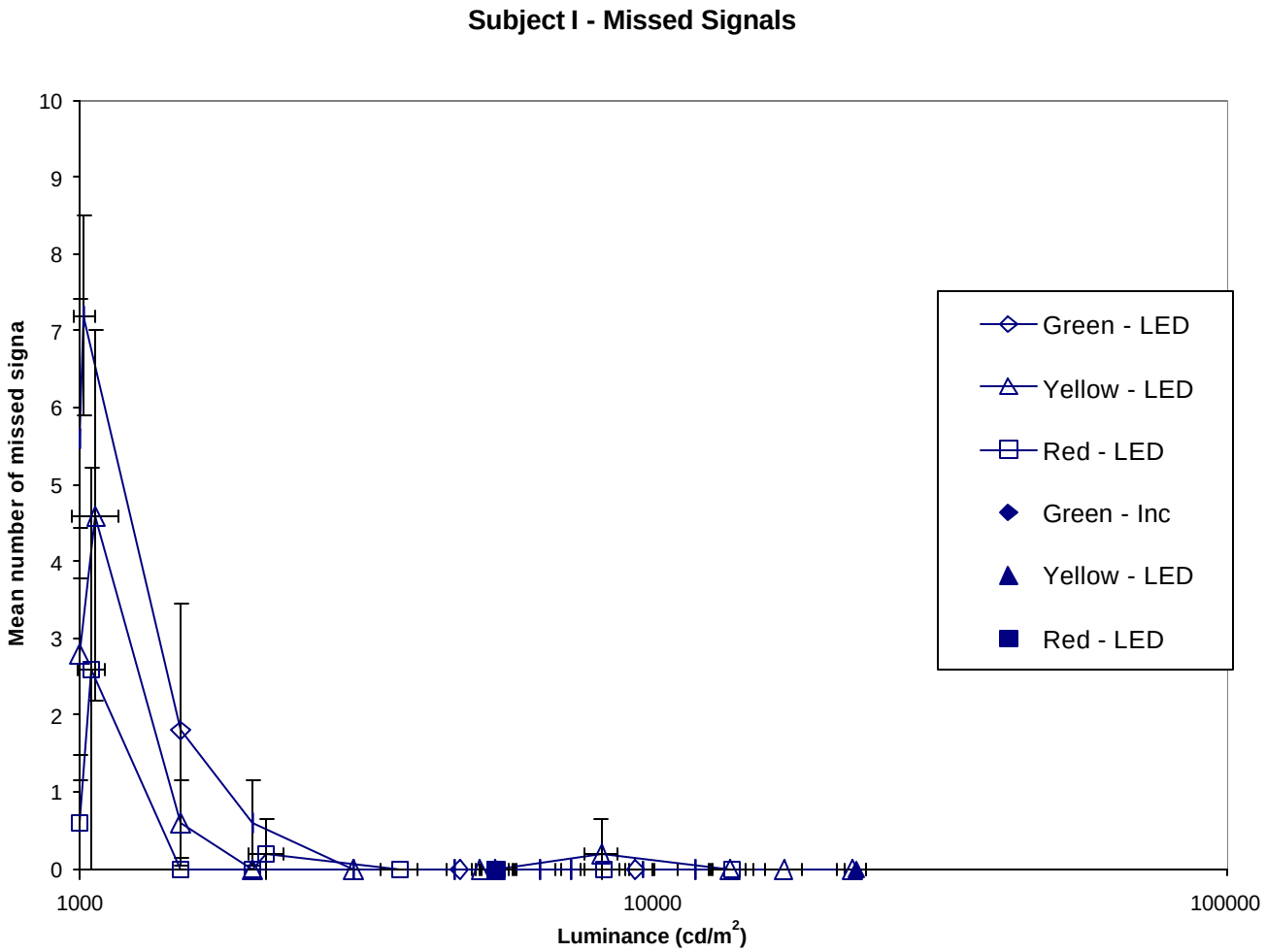

Subject D - Missed Signals
Mean number of missed sign
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc

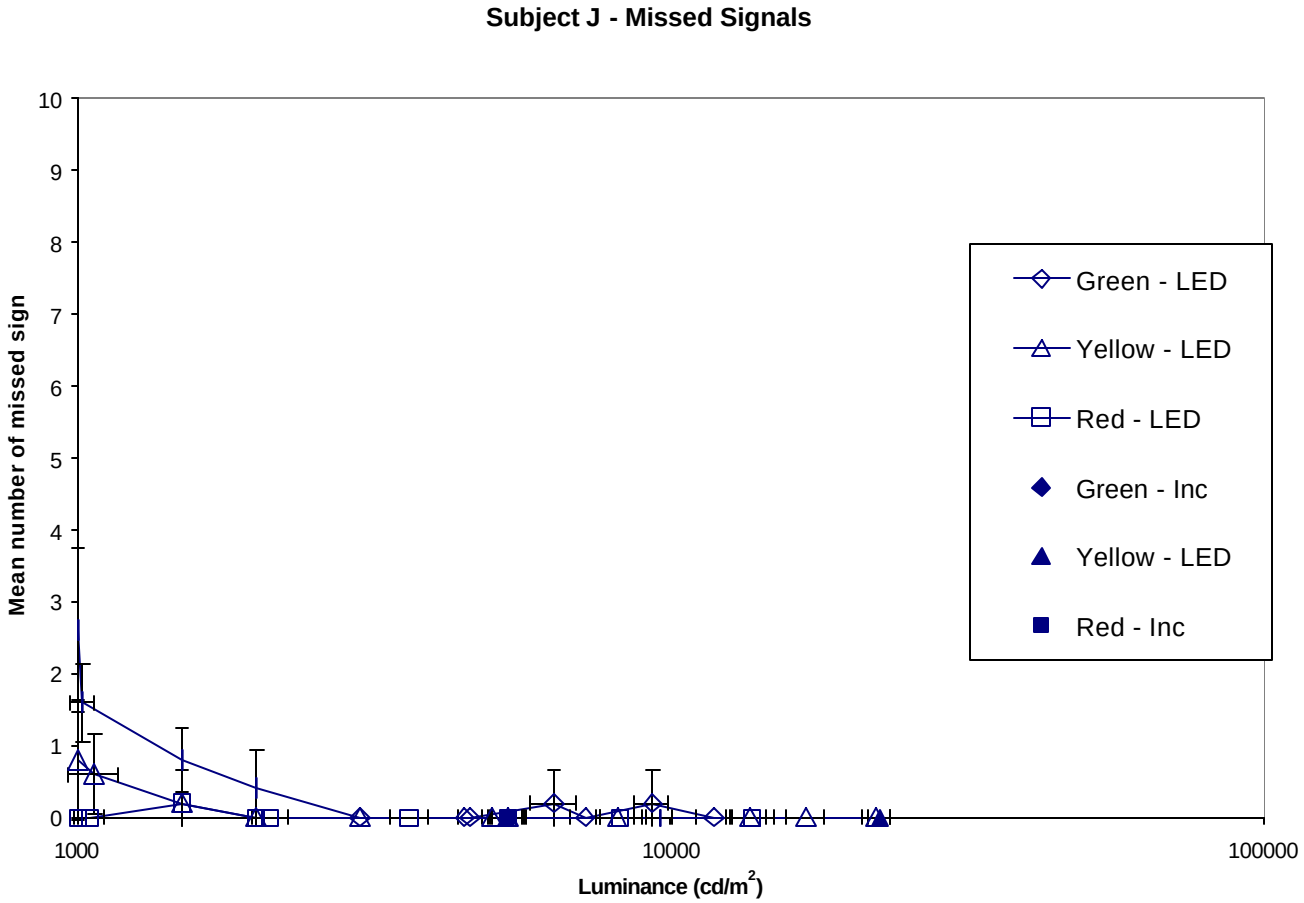

Subject E - Missed Signals
Mean number of missed signa
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc


Subject F - Missed Signals
Mean number of missed signal
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc


Subject G - Missed Signals
Mean number of missed signal
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc


Subject H - Missed Signals
Mean number of missed signa
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - Inc
Red - Inc


Subject I - Missed Signals
Mean number of missed signa
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - LED
Red - LED


Subject J - Missed Signals
Mean number of missed sign
10
9
8
7
6
5
4
3
2
1
0
1000
10000
100000
Luminance (cd/m2)
Green - LED
Yellow - LED
Red - LED
Green - Inc
Yellow - LED
Red - Inc

Appendix 5

Percentage of Missed Signals Predicted from the Best Fitting Equations

The percentage of missed signals for each signal color are predicted from the best fitting equation, for the range of luminances used in the measurements. The best fitting equation for the yellow LED goes slightly negative at luminances higher than 10,500 cd/m^2 (-0.66% at a luminance of 23,500 cd/m^2). As this is impossible, the negative percentages have been replaced with a zero value, above 10,500 cd/m^2.

Luminance (cd/m^2)	Green LED	Yellow LED	Red LED
1000	62	38	12
1500	41	13	3.8
2000	27	7.5	2.3
2500	18	5.1	1.6
3000	12	3.7	1.2
3500	8.2	2.8	1.0
4000	5.8	2.2	0.86
4500	4.3	1.8	0.74
5000	3.3	1.5	0.66
5500	2.6	1.2	0.59
6000	2.1	0.96	0.53
6500	1.8	0.78	0.48
7000	1.6	0.63	0.44
7500	1.4	0.50	0.41
8000	1.3	0.38	0.38
8500	1.2	0.29	0.36
9000	1.1	0.20	0.34
9500	1.1	0.12	0.32
10000	1.0	0.06	0.30
10500	0.94	0.00	0.29
11000	0.89	0.00	0.27
11500	0.85	0.00	0.25
12000	0.80	0.00	0.24
12500	-	0.00	0.24
13000	-	0.00	0.23
13500	-	0.00	0.22
14000	-	0.00	0.21

Appendix 6

Means and Standard Deviations of Ratings of Brightness, Conspicuity and Comfort, for all Three Signal Colors at the Luminances Used.

	Luminance	Brightness		Conspicuity		Discomfort	
Light source	(cd/m2)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
LED - Red	13704	8.00	1.53	8.33	1.42	2.87	1.93
LED - Red	8205	7.13	1.89	7.63	1.94	2.33	1.54
LED - Red	5319	6.77	1.98	7.00	2.07	2.37	1.43
LED - Red	3626	5.97	1.61	6.40	1.75	2.47	1.76
LED - Red	2115	4.70	1.56	4.83	1.70	2.53	1.89
LED - Red	1049	3.00	1.20	3.17	1.42	3.17	2.73
Incandescent - Red	5312	6.17	1.74	6.60	1.77	2.80	1.75
LED - Yellow	22253	7.07	1.41	7.17	1.60	2.57	1.48
LED - Yellow	16895	7.10	1.73	7.27	1.60	2.53	1.63
LED - Yellow	13580	6.77	1.25	6.63	1.43	2.67	1.69
LED - Yellow	8119	5.77	1.50	5.67	1.73	2.77	1.77
LED - Yellow	5321	4.80	1.40	4.73	1.44	3.10	2.17
LED - Yellow	1068	2.07	0.78	1.97	0.96	3.47	3.52
Incandescent - Yellow	22567	6.73	1.57	6.67	1.60	2.47	1.46
Incandescent - Green*	11819	6.10	1.92	5.90	2.04	2.50	1.89
Incandescent - Green*	9334	5.60	1.77	5.40	1.99	2.67	2.04
Incandescent - Green*	7171	5.70	2.25	5.03	2.36	2.87	2.06
Incandescent - Green*	6352	5.10	1.92	4.73	2.03	2.77	1.79
LED - Green	4596	5.13	1.55	4.70	1.64	2.83	2.04
LED - Green	1018	2.07	1.01	2.03	0.96	3.63	3.31
Incandescent - Green*	9587	5.17	2.05	4.53	2.30	2.83	2.31

* Incandescent source filtered to provide similar color to green