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Visual reaction time and size constancy

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Abstract. We carried out six experiments to find out whether simple manual reaction time (RT) to flux-equated visual stimuli of different size is modulated by size constancy or by the retinal angle subtended by the stimuli. We found that RT decreased with the increase in perceived stimulus size rather than retinal angle and that this relationship depended on the use of familiar 3-D-like stimuli and on the availability of other size-constancy cues. Thus, a stereotyped speeded motor response, such as that employed in a simple RT paradigm, is modulated by size constancy, as is the case with perceptual judgments. The present results provide original evidence on the relationship between simple RT and perception.

1 Introduction

A classic finding in experimental psychology is that simple reaction time (RT) decreases as stimulus intensity increases (Exner 1868; Wundt 1874; Cattell 1886; Piéron 1914; see also Pins and Bonnet 1996, 2000). Less is known about the relationship between stimulus size and RT when variations in luminous flux are eliminated. It is usually found that, as the size of simple visual stimuli increases, RT decreases (eg Osaka 1976; Marzi et al 2006) but, to our knowledge, the effect of varying stimulus size while keeping flux constant is unknown. A related, more general, question is whether simple RT reflects size constancy. As is well known, the perceived size of an object is relatively unaffected by substantial changes in viewing distance despite variations in retinal image size. This form of stability of the visual world is commonly known as size constancy and is thought to reflect an active process of re-scaling of size with perceived distance (Andrews 1964; Morgan 1992; Gregory 1997, 1998). The phenomenon was first described by Descartes in his *Dioptrica* in 1637 and, traditionally, size constancy is explained by Emmert's law of 1881, which states that the perceived linear size of an object of constant angular size is directly proportional to its apparent distance. The law was formulated on the basis of the observation that an afterimage looks bigger when fixating on a distant surface than when fixating on a near surface. A more recent account of size constancy is the size – distance invariance hypothesis (SDIH) (Kilpatrick and Ittelson 1953; Epstein et al 1961; Sedgwick 1986). The SDIH is formally equivalent to Emmert's law (Howard and Rogers 2002; Nakamizo and Imamura 2004; Imamura and Nakamizo 2006) and postulates, in a more general form, that perceived size and perceived distance are associated in a way that their ratio is a constant for a given constant visual angle of the object.

Both Emmert's law and the SDIH are based on perceptual judgments. In the present study, we wanted to find out whether a speeded stereotyped motor response to stimuli varying in retinal or perceived size reflects size-constancy laws. To do this we carried out six manual RT experiments in which we manipulated stimulus size, distance, and availability of size-constancy cues while keeping overall stimulus intensity constant.

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2 Experiment 1

The purpose of this experiment was to test, with a simple RT paradigm, the possibility that stimuli of different size, but subtending the same retinal angle as a result of their different distance from the observer, are responded to in relation to their perceived or retinal size.

2.1 *Methods*

2.1.1 *Participants.* Twenty-four healthy right-handed participants (twelve males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 20 and 31 years (mean 26.5 years). In this and in all following experiments participants gave informed consent and the experiments were carried out according to the principles laid down in the 1964 Declaration of Helsinki.

2.1.2 *Apparatus, stimuli, and procedure.* Participants were seated in front of a PC monitor (Sony Trinitron Multiscan E530) in a dimly lit room. The distance between eyes and monitor was kept constant with a chin-rest. The stimulus was a grey luminous dot presented with an exposure duration of 80 ms in the centre of the monitor. Participants were tested in binocular vision and were asked to maintain the gaze steadily on a fixation point (a 0.5 deg grey cross) at the centre of the screen and to respond as quickly as possible to stimulus onset by pressing the spacebar of the PC keyboard with their right index finger. The interval between the disappearance of the fixation point and the onset of the visual stimulus was randomised within the temporal window of 400 – 700 ms. The PC monitor was manually positioned at three possible distances from the participant's eyes: 114, 85.5, and 57 cm. The luminance of the stimuli as measured with a Minolta Chroma Meter CL-200 was adjusted to equate the total luminous flux for stimuli of different size. We decreased the luminance of the stimuli in proportion to the increase in their size by taking the smallest stimulus of the three used in each experiment as 100%. The background luminance was 0.001 cd m^{-2}.

Three kinds of dots were presented: 'small', 1.4 cm in diameter with a luminance of 2.04 cd m^{-2} positioned at 57 cm; 'medium', 2.1 cm in diameter with a luminance of 1.53 cd m^{-2} positioned at 85.5 cm; and 'large', 2.8 cm in diameter with a luminance of 1.02 cd m^{-2} positioned at 114 cm. All stimuli subtended a retinal angle of 0.7 deg.

In this and the following experiments, the stimuli were presented in three blocks of 60 trials (one block for each condition of stimulus presentation) plus 27 catch trials in which disappearance of the fixation point was not followed by target stimuli. Anticipations (RT $<$ 140 ms) and delayed responses (RT $>$ 650 ms) in this and in the following experiments were not included in the statistical analyses. Their proportion was minuscule.

2.2 *Results and discussion*

Figure 1 shows mean RT for each stimulus condition. A one-way analysis of variance (ANOVA) carried out on RT data with size (small versus medium versus large) as factor yielded a non-significant effect ($F_{2,46} = 1.984$, $p = 0.149$). This indicates that RT is not affected by the size of the stimuli when retinal size is kept constant. However, inspection of figure 1 suggests a trend toward faster RT as one goes from small (273.87 ms) to medium (268.84 ms) to large (266.37 ms) stimuli. This RT trend corresponds to the participants' perceptual judgments: when informally asked at the end of the experiment about the size of the three kinds of stimuli they had no doubt in judging them as having their correct size.

One possible explanation of the lack of reliable size-constancy effects on RT in this experiment might lie in the use of schematic non-realistic stimuli. We reasoned that using 3-D-like realistic and familiar stimuli (see Bolles and Bailey 1956; Slack 1956; Schiffman 1967) rather than dots might probably lead to a more efficient operating

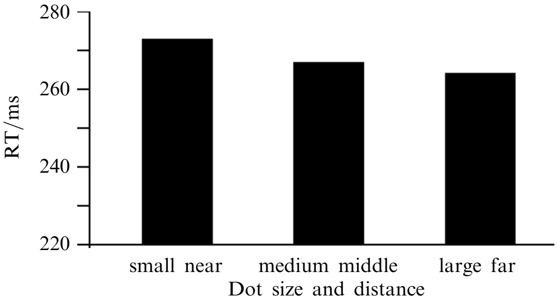

Figure 1. Experiment 1. Dot stimulus: mean RT as a function of stimulus size and distance from observer. The distance was adjusted to keep retinal angle constant. There were no significant differences in RT among the three conditions.

of size constancy with a consequent effect of object size on RT. Interestingly, in a recent brain-imaging paper on the neural correlates of visual size constancy, Murray et al (2006) successfully used 3-D-like spheres rather than standard 'flat' stimuli usually employed in previous experimental-psychology studies. Furthermore, our stimuli were relatively small in terms of the retinal angle subtended, 0.7 deg, and there is evidence from perceptual judgments that size constancy does not operate with precision when the angular sizes are small (Gilinsky 1955; Ross et al 1980; McKee and Welch 1992). In the light of these considerations, in the next experiment we used a similar experimental paradigm as in experiment 1 but with 3-D realistic stimuli subtending a considerably larger retinal angle.

3 Experiment 2

The only difference in this experiment was the change in the visual stimulus. Simple luminous dots were replaced by realistic rendering of a tennis ball which, in addition to being a 3-D object, is a familiar stimulus and this should favour the operation of size constancy (Bolles and Bailey 1956; Slack 1956; Schiffman 1967). If RT is related to perceived rather than retinal size, this effect is more likely to emerge with a realistic familiar stimulus than with schematic stimuli like the grey dots used in experiment 1. In addition, stimulus size was considerably larger than in experiment 1.

3.1 *Methods*

3.1.1 *Participants.* Eighteen healthy right-handed participants (nine males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 18 and 29 years (mean 24.27 years).

3.1.2 *Apparatus, stimuli, and procedure.* The stimulus was a realistic yellowish rendering of a tennis ball presented with different sizes and luminances: 'small', 6 cm diameter with a luminance of 40.8 cd m^{-2}; 'medium', 9 cm in diameter with a luminance of 30.6 cd m^{-2}; 'large', 12 cm in diameter with luminance of 20.4 cd m^{-2}. The background luminance was 96.4 cd m^{-2}. As in the previous experiment, the luminance of the stimuli was adjusted to match the total luminous flux of stimuli of different size. All stimuli subtended a retinal angle of 6.0 deg.

3.2 *Results and discussion*

Figure 2 shows the mean RT for each stimulus condition. Consistent with an increase in stimulus luminance and size, overall RT in this experiment was faster than in experiment 1 (243.37 ms versus 269.69 ms).

Participants responded faster to large (238.43 ms) than medium (243.04 ms) or small (248.65 ms) stimuli. A one-way ANOVA confirmed that size yielded a significant effect ($F_{2,34} = 3.507$, $p < 0.05$).

The result of this experiment indicates that RT is related to perceived rather than to retinal size; it is important to point out that RTs corresponded to the perceptual judgments of stimulus size given by participants at the end of the experiment.

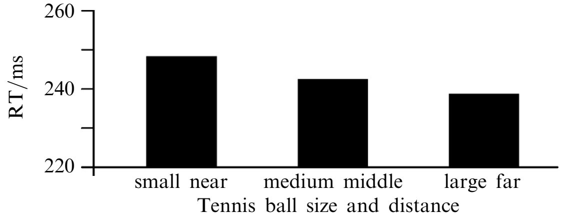

Figure 2. Experiment 2. Tennis-ball stimulus: mean RT as a function of stimulus size and distance from observer. The distance was adjusted to keep retinal angle constant. In contrast to experiment 1 there were reliable differences in RT with stimuli yielding a faster RT as a function of size.

4 Experiment 3

The use of realistic familiar stimuli in experiment 2 enabled a more efficient operation of size constancy in comparison to the simple stimuli used in experiment 1.

One should note, however, that in experiment 2 we manipulated together two variables, namely 3-D appearance and size of the stimuli. To check which of these two factors was crucial in determining a correspondence between RT and perception we carried out a further experiment in which the same group of participants was tested with one or the other variable.

4.1 *Methods*

4.1.1 *Participants.* Six healthy right-handed participants (three males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 22 and 30 years (mean 25.6 years).

4.1.2 *Apparatus, stimuli, and procedure.* Apparatus and general procedure were the same as in the previous experiments.

Each participant was tested in two blocks of trials in a balanced sequence. In block A the same grey luminous dots as in experiment 1 were used but their overall size was as large as the 3-D tennis-ball stimuli of experiment 2 and was scaled with distance to yield a constant retinal angle. In block B we used the same tennis-ball stimuli scaled with distance as in experiment 2 but with an overall small size equal to that of the dots used in experiment 1.

4.2 *Results and discussion*

Figure 3 shows the effect of size and of using 3-D stimuli on RT. Simple inspection of figure 3a shows that increasing the size of the dot stimuli over that in experiment 1

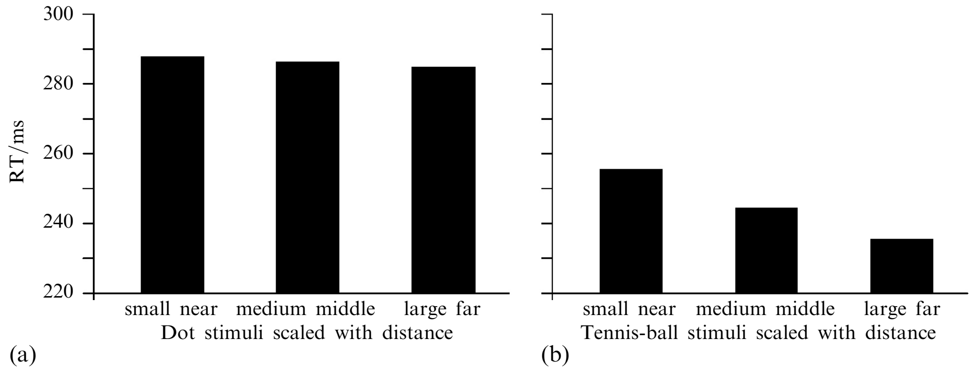

Figure 3. Experiment 3. (a) Dot stimuli of large overall size (as 3-D stimuli used in experiment 2) scaled with distance to yield a constant retinal angle. No reliable effect of size on RT. (b) 3-D tennis-ball stimuli of small overall size (as dot stimuli of experiment 1) scaled with distance to yield a constant retinal angle. RT was reliably faster as a function of stimulus size.

did not yield a perceptual effect on RT. A one-way ANOVA with size as factor did not show any significant effect ($F_{2,10} = 0.038$, $p = 0.9$). In contrast, figure 3b shows that with small 3-D tennis-ball stimuli there was a reliable effect of size on perception. A one-way ANOVA with size as factor showed a significant effect ($F_{2,10} = 9.811$, $p < 0.005$).

The results of this experiment clearly show that 3-D appearance rather than size is a crucial factor for size constancy to operate, in that increasing the size of dot stimuli to match that of the 3-D stimuli used in experiment 2 did not succeed in yielding a perceptual size effect on RT. On the contrary, decreasing the size of 3-D stimuli to match that of experiment 1 did not affect the operation of size constancy found in experiment 2.

5 Experiment 4

To confirm the relationship between perceived, rather than retinal, size and RT, in this experiment we used the same realistic stimulus as in experiment 2 but kept the size fixed while varying the viewing distance with a consequent variation of the retinal angle subtended. If RT reflects the operations of size constancy it should not differ for the three conditions of visual stimulation. The experimental setting was identical to that of experiment 2 except that the size of the stimuli was the same for the three viewing distances. Therefore, the retinal image decreased progressively with increasing distance. If RT is related to retinal size, then it should get progressively longer with increasing distance. Conversely, if RT is related to perceived size, then it should stay the same independently of the viewing distance.

5.1 *Methods*

5.1.1 *Participants.* Twelve healthy right-handed participants (nine males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 19 and 26 years (mean 21.58 years).

5.1.2 *Apparatus, stimuli, and procedure.* The stimulus used was the 'small' tennis ball of experiment 2 of 6 cm in diameter and 40.8 cd m^{-2} luminance. The retinal angles subtended for the three viewing distances were 3, 4.5, and 6 deg.

5.2 *Results and discussion*

Figure 4 shows mean RT for each stimulus condition; a one-way ANOVA showed that distance (near versus middle versus far) was not significant ($F_{2,22} = 0.869$, $p = 0.433$).

This result indicates that RT is unaffected by variation in retinal size in keeping with the participants' perceptual judgments given at the end of the experiment and therefore supports the idea that RT reflects perceived-stimulus size rather than retinal-angle size.

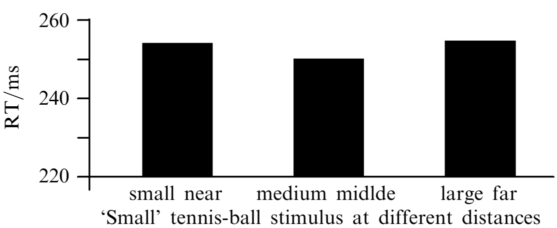

Figure 4. Experiment 4. Tennis-ball stimulus: mean RT as a function of distance from observer when using a stimulus of the same (small) size. There were no reliable effects of stimulus size on RT.

6 Experiment 5

The previous experiments have shown that RT is related to perceived rather than retinal size of an object. To further confirm this finding, in the next two experiments we minimised size-constancy cues by testing participants monocularly and using a pinhole for stimulus viewing.

In a classic experiment, Holaday (1933) found that, when a variety of visual cues were available, perceived size corresponded to the physical size of the object, while when depth cues were removed size judgments tended to conform to a prediction based on visual angle.

Holaday's findings were confirmed by Holway and Boring (1941). In their classic study, participants adjusted the size of a nearby disc to match the size of a distant disc. Visual information was reduced from a 'full-cue' condition to three 'reduced-cue' conditions, namely, monocular observation, monocular observation with artificial pupil, and monocular observation with artificial pupil and reduction tunnel. Holway and Boring demonstrated that, when distance cues were available, perceived size approximated the physical size of the more distant disc rather than its retinal size. However, as distance cues were progressively reduced, participants increasingly tended to match perceived size to retinal size.

In the present experiment size-constancy cues were removed with the use of pinhole and monocular viewing. Under these conditions, when size constancy does not hold, RT should reflect stimulus retinal size only (see Leibowitz and Moore 1966; Ono 1966; Harvey and Leibowitz 1967).

6.1 *Methods*

6.1.1 *Participants.* Twelve healthy right-handed participants (six males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 20 and 30 years (mean 25.08 years).

6.1.2 *Apparatus, stimuli, and procedure.* These were the same as in the preceding experiment except that participants were tested in a completely dark room and viewed the stimuli through a pinhole with an aperture of about 1 mm. The PC monitor was set at 114, 85.5, and 57 cm from the participant's eye. Stimuli were presented in monocular vision by occluding the dominant eye with an eye-patch. Ocular dominance was assessed with the 'hole-in-the-card test', also known as the Dolman method (see Cheng et al 2004). Stimulus size was scaled with distance in order to keep retinal angle constant. We used grey renderings of tennis balls rather than yellow and overall stimulus luminance was decreased to avoid dazzling. As in the previous experiments, stimulus intensity was adjusted as a function of stimulus area in order to obtain the same total amount of flux for the three stimuli of different size. The background luminance was 0.001 cd m^{-2}. The stimulus was presented under three conditions of size and luminance: 'small', 6 cm in diameter with luminance of 7.6 cd m^{-2}; 'medium', 9 cm in diameter with luminance of 5.7 cd m^{-2}; 'large', 12 cm in diameter with luminance of 3.8 cd m^{-2}. All stimuli subtended a retinal angle of 6.0 deg.

6.2 *Results and discussion*

Figure 5 shows mean RT for each tennis ball stimulus condition; simple inspection of the figure indicates that RT does not vary for the three conditions of stimulus presentation.

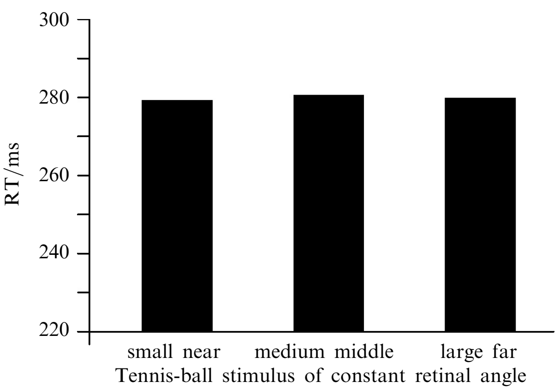

Figure 5. Experiment 5. Pinhole viewing. Tennis-ball stimulus: mean RT as a function of stimulus size and distance from observer. Stimulus size was adjusted to yield a constant retinal angle. No reliable effect of size was found.

A one-way ANOVA showed that the effect of size was not significant ($F_{2,22} = 0.030$, $p = 0.971$). Thus, RT was unaffected by the physical size of the stimuli when depth and distance cues were eliminated. Perceptual judgments given at the end of the experiments were in keeping with the RT data in that participants judged the stimuli as being of the same size.

7 Experiment 6

In this experiment we used a pinhole again as in experiment 5 but kept the size of the stimuli identical for the three viewing distances. Therefore, the retinal image decreased progressively with increasing distance. In this case, a distance effect on RT is expected: RT should get progressively longer with increasing distance because size-constancy cues are not available.

7.1 *Methods*

7.1.1 *Participants.* Twelve healthy right-handed participants (six males) with normal or corrected-to-normal visual acuity took part in the experiment. Their ages ranged between 19 and 26 years (mean 21.58 years).

7.1.2 *Apparatus, stimuli, and procedure.* The experimental conditions were the same as in the previous experiment except that stimulus size was not scaled with distance. The 'small' stimulus of the previous experiment was presented at the three distances with a luminance of 7.6 cd m^{-2}. The retinal angles subtended by the stimuli were 3, 4.5, and 6 deg.

7.2 *Results and discussion*

Figure 6 shows mean RTs for each stimulus condition; simple figure inspection clearly indicates that RT was progressively slower in passing from near (293.09 ms) to middle (305.92 ms) and far (320.51 ms) locations. A one-way ANOVA showed that distance ($F_{2,22} = 13.204$, $p < 0.001$) was highly significant. In keeping with RT data, participants judged the stimuli as progressively smaller when positioned at increasing distance.

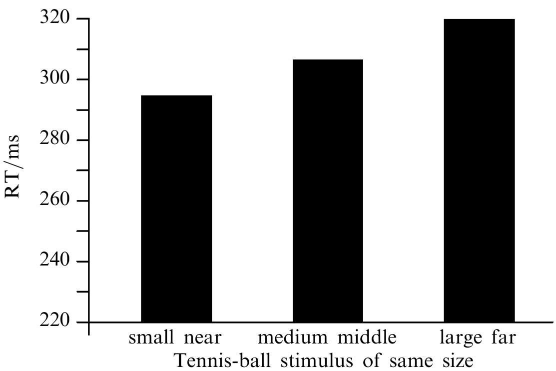

Figure 6. Experiment 6. Pinhole viewing. Tennis-ball stimulus: mean RT as a function of distance from observer of a stimulus of the same (small) size. RT reliably increased as a function of distance.

In the present experiment, distance and depth cues were removed by means of pinhole monocular viewing and stimulus size was not scaled with distance. Under this restricted condition, size constancy failed to keep perceived size constant. As a consequence, RT depended upon retinal stimulus size: more distant stimuli subtending smaller retinal angle were responded to more slowly than less distant stimuli.

8 General discussion

Taken together, the results of the above experiments lead to the conclusion that simple manual RT to the presentation of flux-equated stimuli of different size is related to perceived rather than retinal size. Therefore, one can conclude that simple RT follows the rules of size constancy. The general relevance of this finding is that, at variance with other motor responses to visual stimuli such as reaching or grasping showing a discrepancy between perception and action (see for a recent review Milner and Goodale 2008), simple RT reflects pretty well the perceptual outcomes of the operations carried out by size constancy. We found that the crucial factors determining whether RT reflects perceived size rather than stimulus retinal size are strongly related to stimulus familiarity, with particular reference to 3-D-like appearance. Experiment 3 was specifically run to test whether 3-D or size was important for RT to follow size-constancy rules, and the former turned out to be essential. Obviously, further experiments are necessary to detail the contribution of other aspects of the visual scene.

As to possible neural bases explaining the relationship between simple RT and size constancy, our results are in broad keeping with two recent studies. Murray et al (2006) found with functional magnetic resonance imaging that a visual stimulus subtending the same retinal angle as a similar one but appearing to be located at a greater distance activated a larger volume of the primary visual cortex. By the same token, Arnold et al (2008) found that a classic psychophysical adaptation effect, the tilt aftereffect, which is believed to be subserved by orientation-tuned neurons of primary visual cortex, is not simply related to retinal angle but depends on apparent stimulus size. Both of these results are compatible with the idea that retinal size of an object and distance information are combined early in the human visual system and probably at the level of the primary visual cortex. Of course, it remains to be established how important might be the contribution of top – down influences from higher centres.

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