KATHOLIEKE UNIVERSITEIT LEUVEN

FACULTEIT PSYCHOLOGIE EN
PEDAGOGISCHE WETENSCHAPPEN

Laboratorium voor Experimentele Psychologie

# SENSITIVITY TO NONACCIDENTAL PROPERTIES IN TWO-LINE CONFIGURATIONS

Master thesis submitted
to obtain the degree of
Master of Science in Psychology
by

**Charlotte Sleurs**

Promotor: Prof. Dr. J. Wagemans
Daily supervisor: J. Kubilius

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## Summary

**Sleurs, Charlotte**, Sensitivity to nonaccidental properties in two-line configurations

Master thesis presented to obtain the degree of Master of Science in Psychology
Exam period: June 2014
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Given that we can very easily recognize meaningful objects in our surroundings, the question is how our brain can efficiently translate the two-dimensional input on our retinas into a meaningful three-dimensional object again. To address this question, we discuss which input properties (of simple two-line configurations) are the most salient cues, that could enhance these recovery processes. In this context, two well-known approaches emphasizing the role of regularity, are to be considered.

On the one hand, according to the Minimal Model Theory (MMT) of Feldman (2003), we interpret stimuli in their most simple or regular form (i.e. their 'Minimal Model'). More specifically, he stated that the fewer degrees of freedom remain to construct a two-line configuration (i.e. the more special the two-line-configuration is), the stronger our perceptual grouping for this configuration becomes. On the other hand, the importance of regularity for perceptual organization was also stressed by Biederman (1987). In his Recognition-by-components Theory (RBC) Biederman argued that so-called *Nonaccidental Properties (NAPs)* (i.e. regularities in two-dimensional projections, such as symmetry, parallelism, … ), are essential for object recognition. Although both theories were well supported, sensitivity to these specific regularities has only been documented with two-line and object stimuli, respectively. What is more, comparisons between sensitivity to both classes of regularity (based on 2D and 3D, resp.), were not yet made so far. Hence, to tackle the issue of which features are most informative to our brain in order to group lines or object edges, we conducted two new studies.

In particular, we examined sensitivity to changes in two-line properties (based on the MMT and the RBC-theory, resp.) with a simple visual detection paradigm. Hence, in our first study, two-line configurations were constrained in their degrees of freedom. More specifically, for regular variants, the angle sizes were set to 90 degrees and intersection positions were set to midpoints. Our first study indeed indicated a significant sensitivity to orthogonal angles. Yet, even though we anticipated a faster detection of midpoint intersections, for non-orthogonal angles, intersections towards extremes turned out to be easier instead. Given that the MMT could not account for this, a follow-up experiment was set up, which showed that this effect could be due to perceived changes in junction type. In our second study, two-line stimuli were based on a wider set of earlier investigated nonaccidental properties. Here our results confirmed that changes to all of these properties (i.e. collinearity, alignment, curvature of contours, curvature of configuration axis, cotermination, and junction type) were detected faster than metrically equivalent changes.

In conclusion, our results seem primarily in line with the RBC-theory. Given that the encountered sensitivity to NAPs (in their classical sense) even emerged in two-line configurations, it appears that recovery of 3D properties in the context of 3D object recognition is not even necessary to show their special status in the visual system.

# Prologue

During the past two years I got introduced to vision research for the very first time. Given my choice of Clinical psychology studies, I was not familiar with (statistical) programming, nor with visual processing or its neurological underpinnings, without even mentioning the relevance of two-line stimuli in vision research. Nevertheless, although I was completely unexperienced, I never regretted my choice of this dissertation. Without this particular Master thesis and the thorough guidance of my supervisors, I would never have experienced such a detailed initiation into vision research. Therefore, after a lot of work that was accomplished, I can finally express my gratitude to a couple of people in particular.

This work was supported by a Methusalem Grant (METH/08/02) from the Flemish Government, awarded to professor Johan Wagemans. First of all, I would like to thank him very much for sharing his extensive knowledge and experience in this research domain, for his insightful suggestions on this Master thesis and for the opportunity to present the poster on our findings at the AVA conference. His passionate talks and advices encouraged me to keep working on this manuscript until the very end of this project. Second, I am also extremely grateful to Jonas Kubilius for his excellent guidance during the entire project. He is to be admired for his patience, even after (literally) hundreds of e-mails and talks. Thank you for the profound initiation in analyses and programming in Python, for helping me in developing more sophisticated English and for sharing your insights on this manuscript. Third, I also thank professor Hans Op de Beeck for his time and his efficient comments on this paper. Owing to the professors' and Jonas' passion for vision research, I became fascinated by research throughout this project myself as well.

In addition, besides the hard work that needed to be done, I could always count on my friends from high school and from Leuven. Therefore, I thank all of them for the warm, supportive, interesting, de-stressing and humorous talks and parties during the past five years.

Finally, I also wish to explicitly acknowledge my family, my parents in particular. I thank them for always being there, for their eternal love and support. Although they mostly saw me engaged for school and my internship last year, I know they are very proud of who I am and what I do.

Thank you!

Yours sincerely,

Charlotte Sleurs

June, 2014

## Contribution and approach

After two years of intensive collaboration with my daily supervisor Jonas Kubilius and my promotor Prof. Dr. Johan Wagemans, this work can finally be presented in this manuscript. Thanks to them I received the chance to participate in every step of the empirical cycle for the very first time.
Two years ago, when I met Jonas for the first time, his ongoing experiment was based on an earlier fMRI study (Kubilius et al., 2013). For this experiment, data were already assembled when I started, so that my task initially comprised data analyses with Excel and SPSS. Later on, we discussed these early encountered effects and brainstormed about other kinds of regularity features. These discussions then led us to investigate nonaccidental properties, more in its classical sense, next.

For our second study I designed the two-line stimuli and worked out applicable parameters for each stimulus in a parameter file (.xlsx , e.g. orientation, distance between lines, angle size, ...) after many talks with my supervisors. When this new experiment was constructed in Python by Jonas, I collected the data during summer. Afterwards, all of the analyses were performed once again, only this time in Python. I did not have any experience with this (or any) programming language. So, when Jonas had intensively introduced me into these statistical codes, I could perform more detailed analyses on our datasets as well[1]. During our general analyses, I used SPSS for assumption checks and R for repeated measures ANOVA. Initially we also wanted to link association fields to our results, so I wrote codes in Python to calculate them for two-line stimuli[2].

Besides our brainstorming on our findings and the work on this manuscript, I finally had the opportunity to present our findings at the Applied Vision Association conference in Leuven, for which I designed our poster with Scribus. This Master thesis is written in article format, although stimulus sets and extra analyses are included in the appendices as well, as to provide the reader with further information when preferred. Finally, this research was carried out using as many free and open source software tools as possible, including Python (PsychoPy, pandas, and their dependencies) and R for maximal transparency. Source codes of the two reported studies are available at https://bitbucket.org/qbilius/twolines and data sets are available upon request.

[1] Only the most relevant analyses are mentioned in the article.
[2] These are not mentioned in this manuscript because the values were not convincing to analyze them further.

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## Abstract

According to Gestalt Psychology, elementary visual input (such as line segments) is organized by our visual system towards a coherent whole, called a *Gestalt*. Still, the question remains which regularities are most informative cues for perceptual organization in case of two-line configurations. To address this question we conducted two new studies based on two well-known approaches in this domain. More specifically, with a simple visual detection paradigm we examined sensitivity to changes in regular properties of two-line stimuli based on the Minimal Model Theory (MMT) (Feldman, 2003) and the Recognition-by-Components Theory (RBC) (Biederman, 1987). With our first study we demonstrated a significant sensitivity to orthogonal angles. Furthermore, even though we expected a faster detection of midpoint intersections, a higher detectability was encountered for non-orthogonal stimuli with intersections towards extremes instead. Given that the MMT could not account for this, a follow-up experiment was set up, which showed that this effect could be due to perceived changes in junction type. Finally, results of our second study on a wider range of so-called nonaccidental properties (NAPs, based on the RBC) confirmed that all of these properties (i.e. collinearity, alignment, curvature of contours, curvature of configuration axis, cotermination, and junction type) were detected faster than metric equivalents. In conclusion, our findings indicate sensitivity to orthogonality as well as nonaccidental properties in two-line configurations, which could support the importance of both 2D and implicit 3D information in perceptual grouping, even when we only receive elementary two-dimensional input.



*Keywords: perceptual organization, nonaccidental properties, regularity, feature combinations*

## Introduction

When observing our surroundings, the visual system accumulates a lot of information simultaneously. Yet, from a computational point of view (Marr, 1982), before we can actually recognize an object, our visual system is first required to link the edges of objects and to segment its overall shape from the background. Therefore, an intriguing question is how our visual system has been developed in order to efficiently handle these complex processes. Given our visual system not exactly registers the physical reality, how does our brain process regularities in two-dimensional information projected on our retinas, and recover the corresponding properties in three-dimensional space again? In a first attempt to address this question, Gestalt psychologists stated that our visual system is not simply encoding the absolute values of basic elements, but rather their relative values. More specifically, they formulated the *Gestalt laws of grouping*, in which specific relationships between stimuli are defined (e.g. proximity, good continuation, similarity and common fate) that support perceptual grouping or lead to a coherent so-called *Gestalt* (Koffka, 1935; Wertheimer, 1923).

The idea that our perception of elements depends on the global stimulus configuration was also supported by Pomerantz and colleagues (1977). They demonstrated that metric differences in line configurations were easier (or even more challenging) to detect when they were presented within a larger configuration, which they called *the Configural Superiority Effect* (or *Configural Inferiority Effect*) (Pomerantz & Portillo, 2011). For instance, participants could notice a difference in line orientations faster when these lines were part of a triangle than when they were shown separately. Additionally, Kubilius and colleagues (2011) recently demonstrated that this effect correlated with activation in object-related areas, but not in lower visual areas. Similar Gestalt effects were also shown in dot patterns with biological motion experiments (Tadin et al., 2002; Poljac et al., 2012). Bearing this evidence on emergent features in mind, we raise the question which features in configurations consisting of only two lines, lead to perceptual grouping and thus to similar configural effects. For instance, which of the two-line stimuli shown in Figure 1 are perceived as more coherent than other ones?

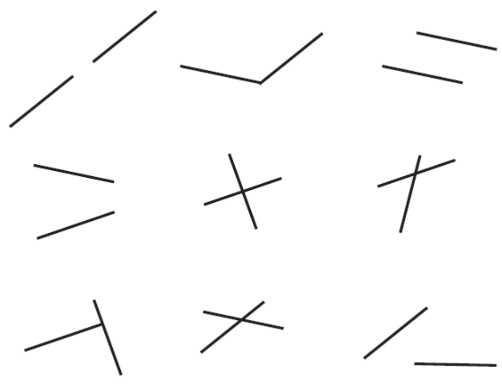

*Figure 1.* Examples of two-line configurations.

In order to clarify this issue, we consider two main approaches. On the one hand, researchers investigated simplicity and *Gestalt* factors in line-configurations in a two-dimensional space (Feldman, 1996, 1997, 2007; Field et al., 1993; Hess et al., 2003). On the other hand, evidence was primarily rendered on grouping of edges in the context of three-dimensional object recognition (Biederman, 1987). We will further discuss these two general approaches and demonstrate in which way they are compatible.

First, in the context of perceptual grouping of two lines, a well-known theory was recently formulated by Feldman (2003). In his Minimal Model Theory, Feldman stated that for each constraint (or decrease in degrees of freedom) that is posed on a configuration, a higher so-called codimension is reached (see Figure 2). According to this theory, we interpret the stimulus in its most regular form (i.e. the least "accidental interpretation"), corresponding to the applicable codimension. For example, for two lines to be parallel, a constraint on the orientation of at least one line is required. Since constraining the position or orientation of one line implies a decrease in its degrees of freedom (or in genericity), Feldman proposed that two parallel lines are perceived as more salient and coherent configurations than generic lines.

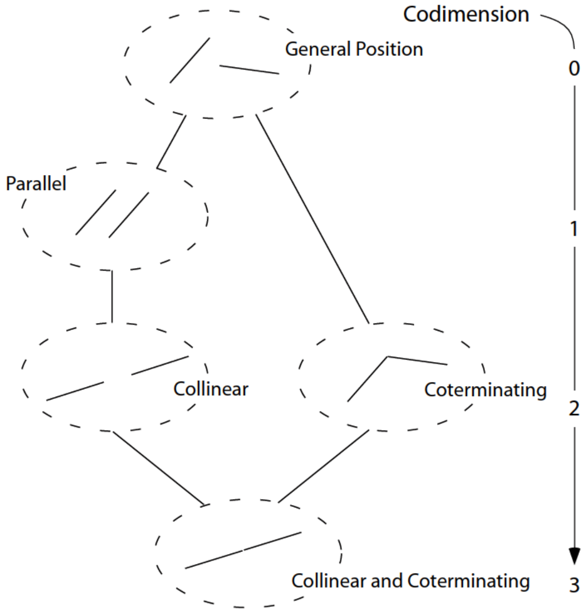


*Figure 2.* Hierarchy of regularity in two-line stimuli according to the MMT (Feldman, 2007).
Note. For each decrease in degrees of freedom a higher codimension of two lines or regularity level is reached.

According to the MMT, this higher level of regularity provokes stronger perceptual grouping (i.e. a "Minimal Model"). Therefore, Feldman and other researchers investigated many metric features of two-line configurations that possibly lead to perceptual grouping (e.g. specific angle sizes, segment lengths and their relative orientations) (Burns et al. 1993; Motoyoshi & Kingdom, 2010; Field et al., 1993). However, even though evidence on perceptual grouping was found for some of these features, extra assumptions about the external world are probably necessary to recover 3D from 2D information (Helmholtz, 1925).

Other theorists thus rather stressed the importance of implicit inferences about the three-dimensional space. For instance, some researchers claimed that the statistical occurrence of edge properties may be an essential factor in this recovery process (Ben-Arie, 1990; Biederman, 1987;

Sigman et al., 2000; Elder & Goldberg, 2002; Jacobs, 2003; Chen, 2005; Claessens & Wagemans, 2008). More specifically, they suggested that the higher the chance to perceive an edge property in a particular way (i.e. the less 'coincidental' it is), the more certain we are to infer that this property is identical in 3D. Although a single 2D image can always result from several different 3D situations (i.e. the fundamental problem of underdetermination), there are particular regularities in the 2D projections of edges that are unlikely to occur by accident. So, when they are present, one can use them to recover similar 3D properties, at least under the assumption of a general viewpoint. For this reason, they were called *Nonaccidental Properties* (NAPs; Lowe, 1985). Examples of NAPs include curvilinearity, collinearity, cotermination, parallelism and symmetry. By contrast, our perception of angle sizes, curvature and an objects length depends on the observer's viewpoint (Biederman & Gerhardstein, 1995; Burns, 2001).

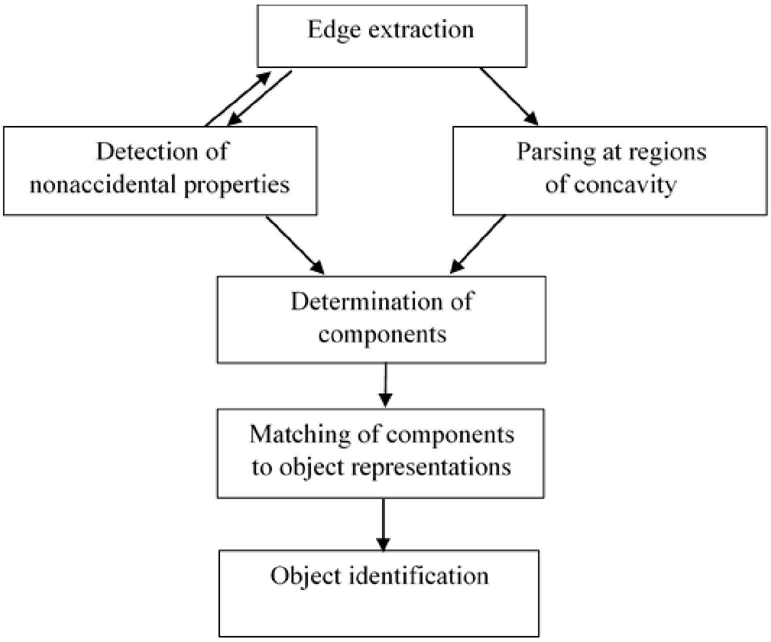


*Figure 3.* Stages in object recognition according to the RBC-theory (Biederman, 1987).

Later on, Biederman (1987) incorporated the NAP-concept in his 'Recognition-by-Components theory' (see Figure 3). In this theory he stated that object recognition relies on a small subset of 3D geometric primitives, called geons, that are derived from nonaccidental edge properties (e.g. a brick or cone) (Biederman & Gerhardstein, 1995). Since our visual system appeared very sensitive to NAPs (Wagemans, 1992; Amir et al. 2012), these basic shapes could be seen as essential elements in three-dimensional object recognition. A brick and a pyramid for instance differ in parallelism as nonaccidental feature and are thus rarely confused in their 2D projection. Besides the importance of NAPs in object recognition, changes in these properties in geons were also discovered to induce a higher neural response in object-related areas in monkeys and humans (Kayaert et al., 2003; Biederman et al., 2004; Kayaert et al., 2005; Kim & Biederman, 2012; Vogels et al., 2001). Later on, this effect was also demonstrated for changes in NAPs in realistic objects (Kayaert et al., 2004) and in match-to-sample tasks, participants generally responded faster to both 2D and 3D geons differing in a wide range of NAPs (Amir et al., 2011; Todd et al., 2014). Based on these findings, the human visual system thus seems remarkably sensitive to these properties. In addition, also children (Kayaert & Wagemans, 2010; Ons & Wagemans, 2011), members of the Himba tribe in Namibia (Biederman et al., 2009), even non-mammalian animals (Gibson et al., 2007; Lazareva et al., 2008; Peissig et al., 2000) show similar detection and recognition effects of NAPs, so that an evolutional sensitivity to these so-called NAPs seems conceivable.

Although many researchers pointed to the general importance of viewpoint-independence in object-recognition, Vanrie and colleagues (2000, 2001) showed that circumstances may differ in which we rely on viewpoint-dependence versus -independence. More specifically, they showed that when basic geometric structures differed in their junction positions due to mirroring, response times for matching target stimuli depended on their difference in rotation (suggesting mental rotation as a process). When the angle of multiple junctions was manipulated (from orthogonal to skewed, a NAP) by contrast, equal response times were encountered for all differences in orientation between the targets (suggesting the use of invariants or NAPs as a process). Therefore, it seemed interesting to us how our visual system would handle changes in 2D presented line segments, either based on viewpoint-dependent regularity vs. viewpoint-independent features. Some theorists already hypothesized that an automatic interpretation of objects from a 2D-drawing was based on the line segments and their junction types in boundaries (Barrow & Tenenbaum, 1981; Van Lier et al., 1994). Hence we conducted two new studies to investigate perceptual sensitivity to different regularity features of two-line configurations.

In our first study, we explored sensitivity to constrained orthogonal angles and midpoint intersections, based on the Minimal Model Theory of Feldman (2003; see Appendix 1). These 2D features are viewpoint-dependent. Furthermore, although the evidence on detectability of NAPs in geons was already established, it remains unknown at what level of the visual information processing such sensitivity emerges. Perhaps the encoding of nonaccidental features is already existing for two-line projections. Therefore, we investigated whether these configurations could already exhibit differences in sensitivity to nonaccidental and metric properties in our second study. These manipulations were based on earlier investigations on NAPs by Biederman (1987) (i.e. junction type, collinearity, alignment, curvilinearity, expansion and cotermination). In this way we wanted to bridge the gap between regularity in line segments (2D) and the importance of this regularity in object reconstruction (3D).

To test participants' sensitivity to different regularities in both of our studies, we implemented a visual detection paradigm. Participants were asked to indicate which stimulus out of four was different. In each condition a base stimulus was changed towards one 'nonaccidental variant' and one 'metric variant' (both equidistant in metric space). In this way, we attempted to clarify relationships between metric and psychological distances (Shepard, 1987) for these two-line variants. More in particular, although both NA and M variants were equally distanced from the base stimulus in metric space, we expected NA variants to be detected faster because of a larger psychological distance from the base stimulus (i.e. a larger perceived difference reflects a larger dissimilarity).

## Study 1

With our first study we aimed to clarify perceptual sensitivity to differences in regularity degrees, based on the Minimal-Model-Theory (MMT) of Feldman (2003). Moreover, starting from this theory, a new hierarchical model was proposed by Kubilius and colleagues (2013; see Figure 1 in Appendix A), which we validated with this new behavioral study.

### Experiment 1A

**Methods**

Experiments and analyses were coded in Python 2.7 using PsychoPy (Peirce, 2007; Peirce, 2009), psychopy_ext (Kubilius, 2014) and pandas packages. Full source code of the experiments are available at [https://bitbucket.org/qbilius/twolines](https://bitbucket.org/qbilius/twolines). Coded analyses were also manually validated with SPSS.

**Participants.** Nine psychology bachelor students (age: 18-19; males: 4, females: 5) at the University of Leuven participated in our first experiment. All participants had normal or corrected-to-normal vision and participated to obtain credits in their bachelor program. In the control experiment, 17 new participants were recruited in the same manner. In contrast to the first experiment, these participants were tested collectively in a PC classroom. Both experiments were approved by the ethical committee of the Faculty of Psychology and Educational Sciences at the University of Leuven.

**Stimuli.** As already mentioned above, a new hierarchical model was constructed considering regularity in two-line configurations (see Appendix A). Given Feldman's theoretical framework (MMT), each constraint in degrees of freedom in our pairs of lines would lead to a higher degree of regularity. More specifically, in our case constraining the angle size and position of intersection (to 90° and midpoint) of the two-line stimuli would result in a more regular variant, which we will call the 'nonaccidental variant'.

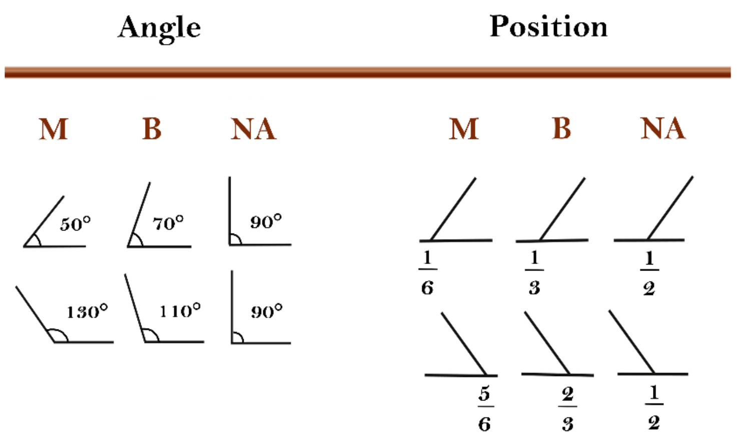


*Figure 4.* Two types of manipulations in our two-line stimuli based on the MMT.

Note. Angle size was altered starting from a 70 or 110 degree base angle towards an orthogonal nonaccidental variant on the right and an equidistant metric variant on the left (- and + 20 degrees, resp.). The second manipulation comprised change in intersection towards the extreme or midpoint (- and + 1/6 of the total segment length, resp.).

Starting from L-, T- and X-junctions as possible configurations consisting of two straight line segments, a large stimulus set was compiled with manipulations in either the angle size or position of intersection between the two lines (see Figure 4 for the logic and Figure 1 in Appendix A for the complete hierarchy of relations). 12 possible changes between these two-line configurations were used to design our main conditions. Each of the 12 conditions thus comprised either a manipulation in angle size or in position of intersection, while the remaining feature was varied within each condition (for the entire stimulus set, see Figure 1 in Appendix B).

For each comparison, a base two-line stimulus (B) was modified in terms of its level of regularity towards a nonaccidental variant (NA) on the one hand and a metric variant (M) on the other hand. The regular variant was called nonaccidental because a higher regularity level of the hierarchical model is reached and exactly one two-line configuration could be generated with an orthogonal angle or midpoint intersection, which is unlikely to happen 'by accident'. From that perspective we expected our visual system to be remarkably sensitive to these changes. The nonaccidental variant was thus constructed with an orthogonal angle or intersection at the center of the horizontal or vertical line. The corresponding 'metric' variant on the other hand was composed with a sharper (or more obtuse) angle or an intersection located more towards the extremity of the horizontal (or vertical) line, respectively. Both variants were edited with the same metric distance from the base stimulus. For each triplet, angle size was manipulated with an extent of 20 degrees, while positions of intersection were ranged between 1/6 and 5/6 with an increase of 1/6 per variant within one triplet of compared variants (see 'Discussion').[3] Variation in angle size and in intersection position (horizontally as well as vertically) resulted in 40 different comparisons. Subsequently, after mirroring all triplets, the entire stimulus set consisted of 80 comparisons. However, due to a small omission, the triplets of two-line stimuli were not mirrored in the first condition (L-junctions) for our main experiment. So during this experiment only 78 comparisons were carried out. Finally, the size of stimuli was 3° in visual angle (vertically and horizontally). These were located with a distance of 3° from the center of the screen in the main experiment, whereas in the control experiment the size of stimuli was 6° in visual angle and distances from the center were 5°. To avoid regularity effects in the overall configurations of the stimuli (sets of 4 two-line stimuli), the position and orientation of these basic stimuli were jittered (.25° and 5° respectively).

**Task.** All basic stimuli consisted of pairs of two line segments, connected in particular ways. Four of these pairs were presented on the PC screen simultaneously (i.e. quadruplets). Each one of them was presented in a different quadrant (see Figure 5). Three of these basic stimuli were identical, while the remaining one was different. In each trial the base stimulus of a triplet was shown (as target or distractor) and opposed to a metric or nonaccidental variant (as distractor or target, resp.). Participants

[3] We assumed that these step sizes are clearly detectable in these stimuli during our experiment. We also assumed that the chosen step sizes would be sufficiently comparable between stimulus triplets.

were requested to observe the quadruplets and indicate which one of the four quadrants contained the odd two-line stimulus as quickly and as accurately as possible, using numbers 1 to 4 on the keyboard.

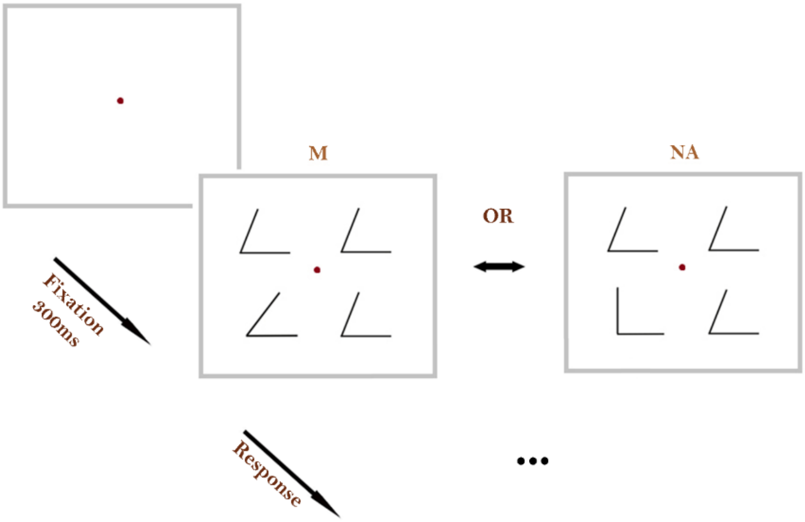


*Figure 5.* Trial sequence.

Note. A fixation spot was initially presented which disappeared after 300 milliseconds. Four stimuli were subsequently shown and participants indicated which one was different. After having responded a next fixation spot was displayed etc. Notice that one trial comprised either a metric or a nonaccidental difference. In this figure the base stimulus is represented as distractor stimulus, while the target variant is detectable in the lower quadrant on the left. In the experiment, all stimuli were white and were presented on a grey background.

For each triplet of variants (i.e. M, B, NA) we manipulated the position of the target within the quadruplet (four quadrants) and whether the base stimulus was set as target or as distractor (either the metric or nonaccidental variant was thus designated as distractor or target stimulus). The two-line stimuli that we created, consisted of white line segments and were displayed against a grey background.

**Stimulus presentation.**

*Main experiment.* In the first experiment, trials were presented in a completely random order. Furthermore, since every possible presentation was shown once throughout the entire experiment, the resulting number of trials was 1248 in total (i.e. 78 comparison types x 2 metric vs. nonaccidental variant x 2 target vs. distractor x 4 target positions). This experiment lasted approximately an hour and a half to complete. Every half an hour, the participant had the option to have a short break.

*Control experiment.* While in the main experiment no fixed schedule in presentation of trials was set, we now employed a blocked design in order to obtain optimal levels of performances. Like this, participants could get used to detection of specific features and therefore handle the most clean, efficient detection strategies. Trials were blocked by type of manipulation this time (angle/position of intersection for non-orthogonal stimuli/position of intersection for orthogonal stimuli). Within each block, the order of the concerning conditions was random. Not only this change in design could thus help participants to become accustomed to search for specific features, the four basic stimuli were also explicitly numbered throughout the second experiment to facilitate response key mapping. Furthermore, due to time constraints this experiment was abbreviated. More specifically, three out of eight possible quadruplets (i.e. 4 target positions x 2 target vs. distractor) were randomly assigned to our participants. In other words, participants only observed three repetitions of each comparison type instead of eight this time, with a random assignment of this target position and whether the base stimulus was a target or a distractor. Consequently, these participants were exposed to 480 trials in total (i.e. 80 comparison types x 2 metric x nonaccidental x 1/3 [2 target vs. distractor x 4 target positions]). The duration of this experiment was approximately half an hour.

**Results**

Our main prediction was that reaction times would be smaller for distinctions between nonaccidental variants and base stimuli than for detection of other metric changes, because of a larger expected psychological distance between base stimulus and NA-variant. Before performing paired samples t-tests[4] with regard to metric vs. nonaccidental differences, distributions of reaction times were separately examined with QQ-plots (see Figure 4 in Appendix C) in order to check the assumption of normality. As expected, response times were not entirely normally distributed. Therefore, we analyzed the participants' median reaction times instead of mean values. Furthermore, we only included the correctly responded trials in the analyses. To verify the homogeneity of variances, a Levene's test indicated that variances of metric and nonaccidental conditions did not reach significant levels of dissimilarity ($F(1,214) = 3.49$, $p = .06$). Finally, bean plots per condition provided a more detailed estimation of these assumptions and could support our previous selection of corrections (see Figure 5 in Appendix C).

Eventually, paired samples t-tests were performed, which indicated robust effects for nonaccidental changes in angle size before corrections were applied (condition 1, $t(8) = 5.11$, $p < .001$; condition 2, $t(8) = 4.76$, $p = .0014$; condition 3, $t(8) = 3.46$, $p < .01$; condition 6, $t(8) = 4.37$, $p < .01$; condition 7, $t(8) = 4.36$, $p < .01$; condition 8, $t(8) = 2.30$, $p = .0501$; see Figure 6). Yet, Bonferroni correction[5] reduced these effects to non-significant for two of these conditions (i.e. conditions 3 and 8). On the contrary, no significant effects were found for changes in position of intersection in orthogonal stimuli (condition 5, $t(8) = .08$, $p = .94$; condition 10, $t(8) = -1.10$, $p = .30$; condition 12, $t(8) = -0.25$, $p = .81$). Although one could assume the absence of sensitivity to changes in positions in general, reversed effects were noticed for changes in position in non-orthogonal stimuli (condition 4, $t(8) = -3.43$, $p < .01$; condition 9, $t(8) = -4.49$, $p < .01$; condition 11, $t(8) = -2.55$, $p < .05$). In other words, in these cases we appeared to be sensitive to intersections towards extremes instead of midpoints. However, after Bonferroni adjustment this effect remained significant for only one condition (i.e. condition 9).

[4] Since we were mainly interested in the effect of distance (metric versus nonaccidental differences) on response times, the choice of paired samples t-tests seemed most legitimate to us.
[5] Original *p*-values are mentioned in the main text. After Bonferroni adjustment, critical *p*-values 05, .01, .001 became $p = .05/12 = .0042$; $.01/12 = 8.3 \times 10^{-4}$; $.001/12 = 8.3 \times 10^{-5}$, respectively (see Figures).

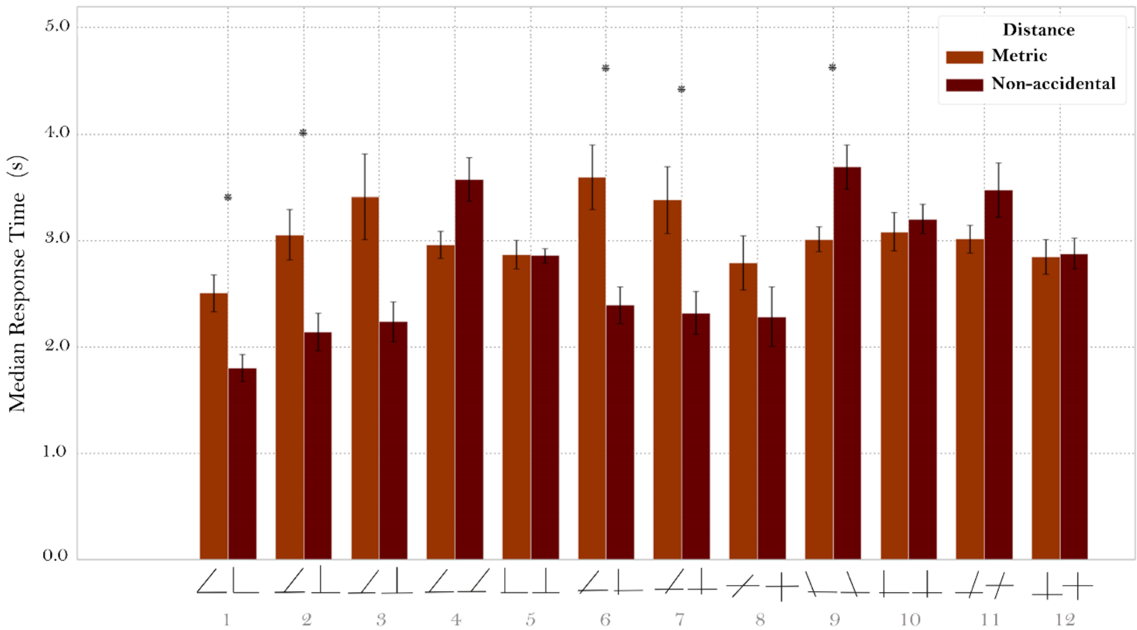


*Figure 6.* Average median response times during the main experiment.
Note. Error bars denote standard errors of means across participants ($n$ = 9).
* = $p$-value significant at α-level = .05 (Bonferroni corrected)

Given that the effects in our main experiment were not always in the direction of what we had expected, the question whether this could be due to differential learning of trials was raised. To investigate if our findings would be replicated when the participant was equally trained in all conditions, we implemented a blocked design. Results of this control experiment confirmed our earlier significant effects (see Figure 7). In addition, significant effects were now also encountered for conditions 3, 4 and 8 (resp. $t(16) = 3.44$, $p < .01$; $t(16) = -5.23$, $p < .001$; $t(16) = 3.55$, $p < .01$), which strengthened a threefold distinction between the conditions (see further). This time, all of the effects remained statistically significant after Bonferroni correction[6]. Finally, the null results for conditions 5, 11 and 12 were replicated as well, so that sensitivity to changes in position of intersection appears to be limited to non-orthogonal stimuli. However, one significant effect for position change in orthogonal stimuli was found for condition 10 ($t(16) = -3.48$, $p < .01$).

Something that should be noticed in general is that response times were on average comparable between metric conditions, whereas large differences existed between response times for nonaccidental changes, which may mainly have led to the significant effects (see 'Discussion').

[6] After Bonferroni adjustment, critical $p$-values of .05, .01, .001 became $p = .05/12 = .0042$; $.01/12 = 8.3 \times 10^{-4}$; $.001/12 = 8.3 \times 10^{-5}$, respectively.

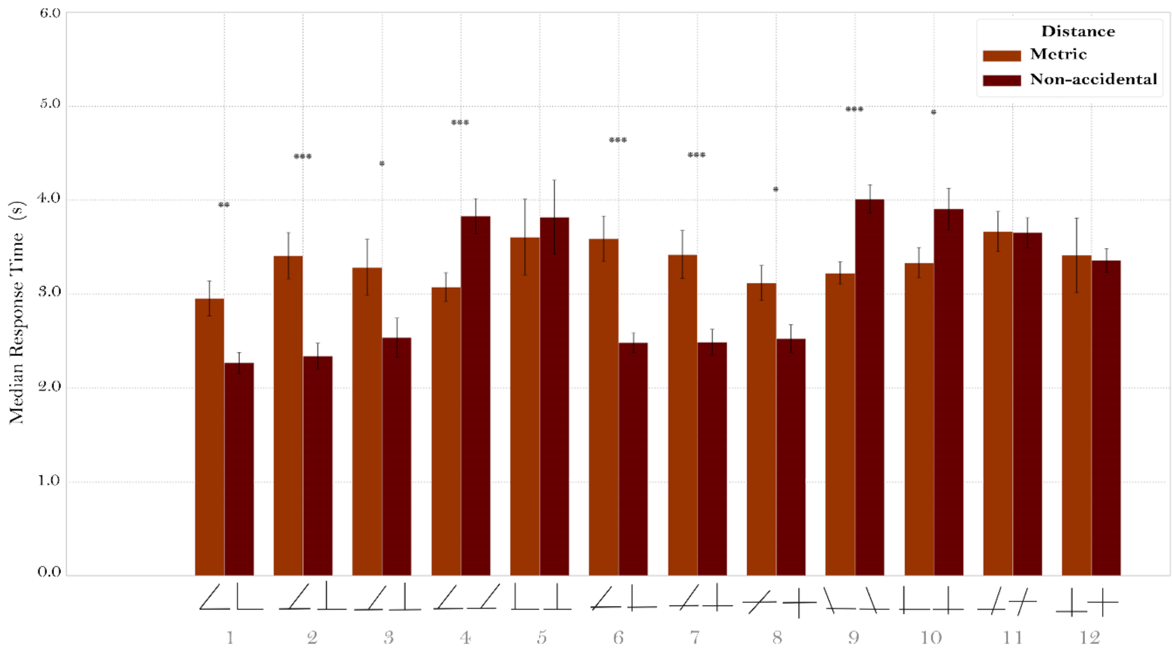


*Figure 7.* Average median response times during the control experiment
Note. Error bars denote standard errors of means across participants ($n$ = 17). * = $p$-value significant at α-level = .05; ** = $p$-value significant at α-level = .01; *** = $p$-value significant at α-level = .001 (after Bonferroni correction).

To investigate whether response times were indeed clearly dividable by the three subclasses of manipulations (i.e. angle size, position in non-orthogonal stimuli, position in orthogonal stimuli) based on the hierarchical framework of Kubilius et al. (2013), new analyses were performed. As shown in Figure 8, clustered results could indeed support this hypothesis about a threefold distinction. However, as already mentioned, these results were not entirely corresponding to what we initially expected.

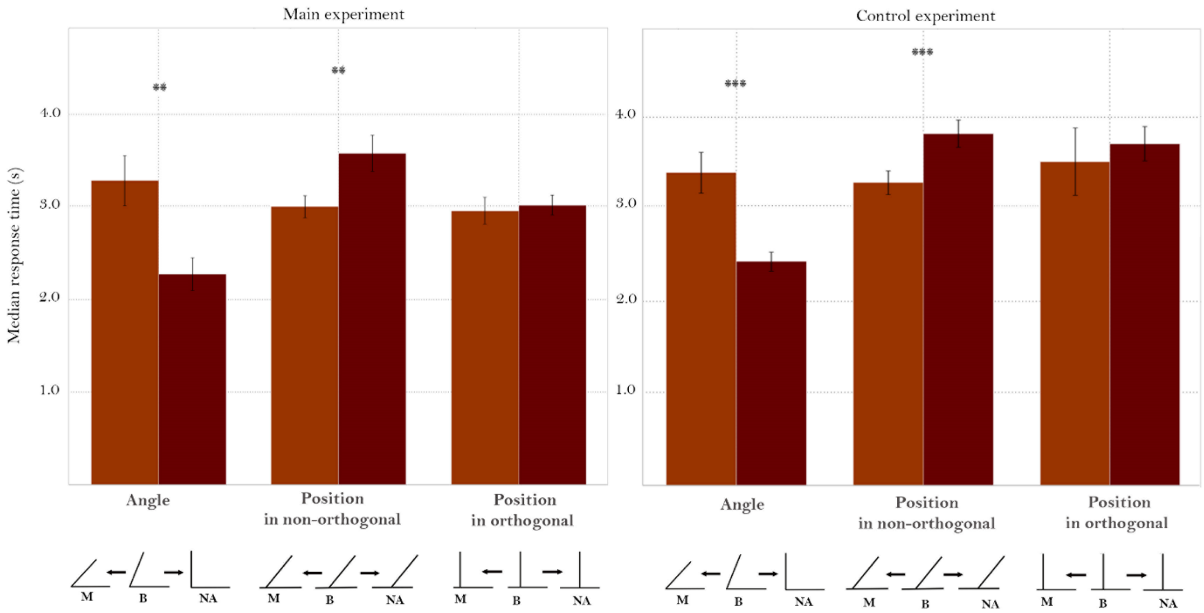


*Figure 8.* Median response times averaged for each manipulation category.
Note. Error bars denote standard errors of means across participants ($n$ = 9, $n$ = 17, respectively). From left to right: $t$-values = 4.53, -4.00, -0.58; 6.83, -5.68, -0.58 with p-values of .0019, .0039, .5774; 4 x $10^{-6}$, 3.4 x $10^{-5}$, .5671, respectively. ** = $p$-value significant at α-level = .01 ; *** = $p$-value significant at α-level = .001.

More specifically, changes in angle size did indeed result in shorter reaction times when detecting the nonaccidental variant. By contrast, reversed effects and null results are to be noticed for changes in position in non-orthogonal and orthogonal stimuli, respectively. Since we expected shorter reaction times for detecting the variant with midpoint intersections, these results are rather remarkable.

## Experiment 1B

With regard to our findings in Experiment 1A, the question may rise whether the inconsistent and reversed effects of changes in intersection position could be explained by a perceived change in junction type (i.e. towards a coterminating junction type in the metric variant), instead of perceived change in position. To be able to answer this question, we conducted a follow-up experiment in which three stimulus sets (based on the previously assumed threefold partition of conditions) were constructed with gradual changes in junction type.

### Methods

Experiments were coded in Python 2.7 using PsychoPy (Peirce, 2007; Peirce, 2009) and reported analyses were performed with SPSS.

**Participants.** In this experiment 15 participants were randomly assigned to one of three distinct conditions. Four participants took part in our first condition, seven of them were exposed to stimuli of our second condition and the remaining three participants were assigned to the third condition.

**Stimuli.**

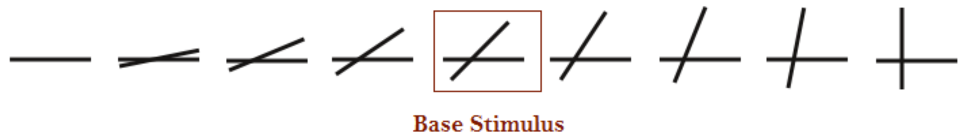


*Figure 9a.* Stimuli condition 1

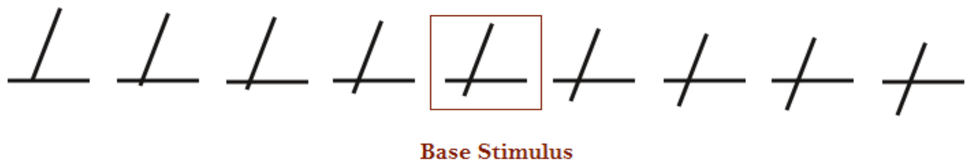


*Figure 9b.* Stimuli condition 2

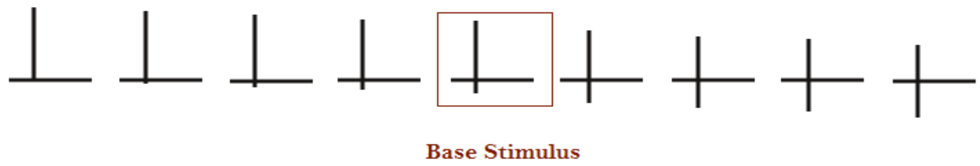


*Figure 9c.* Stimuli condition 3

*Figure 9.* Stimulus dimension for each condition in Experiment 1B.

With this follow-up investigation we wanted to gain insight into the finer scale differences for each of the three general stimuli categories (orthogonality, intersection at midpoint in non-orthogonal stimuli and intersection at midpoint in orthogonal stimuli). Instead of comparing all stimuli, we kept the base stimulus fixed and presented this one simultaneously with one of the variants from the same dimension (see Figure 9). As shown in this figure, three dimensions were arranged by either angle size (for orthogonality as NAP) or by position of intersection (towards midpoint). By using these dimensions for our conditions, we can easily compare reaction times over different junction types. Given our results of Experiment 1A (i.e. sensitivity to orthogonal angles and to intersection positions towards extremes in non-orthogonal stimuli, whereas no effect was found for orthogonal stimuli), we would expect a convex-like trend, a concave-like trend and a stable linear trend for response times to variants on the right half of the dimension, respectively.

**Task.** The task of this experiment was comparable to Experiment 1A. One odd stimulus was to be detected out of four configurations. Participants were this time limitedly exposed to merely one stimulus dimension: 8 (stimulus range) x 4 (target position) x 2 (target vs. distractor) x 7 (runs), resulting in 448 trials. Again the experiment took approximately half an hour for participants to complete.

**Results**

First, as shown in Figure 10, for each dimension reaction times were consistently smaller for detection of the first variant of the range (i.e. the two-line stimulus with a metric distance of -4 from the base stimulus). Given that his variant is different in junction type from the base stimulus, this finding could confirm sensitivity to nonaccidental change in junction type. What is more, this could also support our post-hoc interpretation of the reversed effects for change in position in experiment 1A (i.e. the metric two-line variant being perceived as two coterminating lines). Second, differences in slopes of the interpolated curves for reaction times could be noticed as well, although the interpretations could be rather speculative. More specifically, the largest slope of the first curve on the left side as well as on the right sight indicates sensitivity to changes in angle size, which was also demonstrated earlier in our first experiment. Furthermore, the second curve is ascending more gradually on the left, whereas reaction times for variants on the right of the dimension do not differ to this extent. This could confirm a stronger sensitivity towards cotermination (on the left) than towards midpoint intersections. Additionally, the smallest slope of the third curve could support the lack of effect when altering position of intersections in orthogonal stimuli as well, since these differences appear to be very small (see ‘Discussion’). Finally, reaction times are on average the lowest for the second condition. This latter finding might again be indicative of difficult detection of intersection positions in non-orthogonal stimuli.

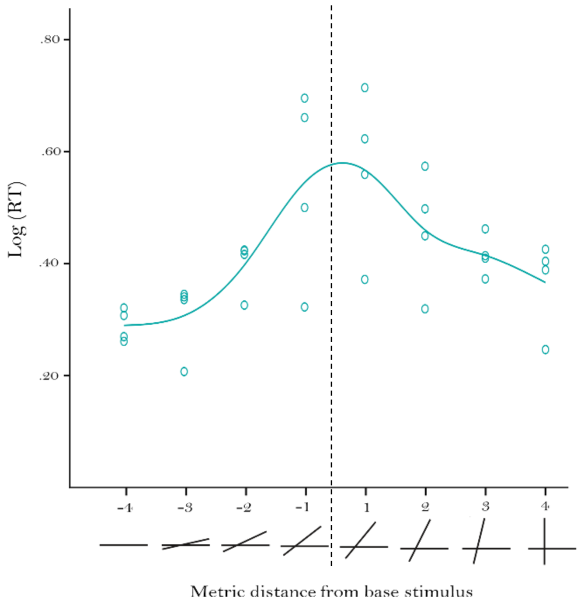


*Figure 10a.* Results condition 1

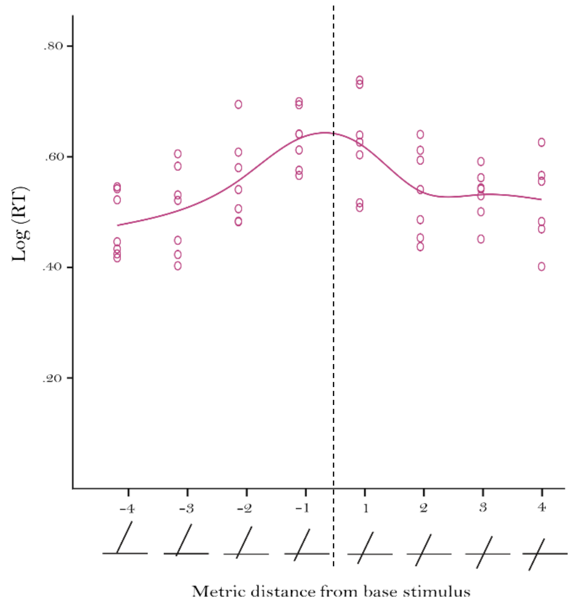


*Figure 10b.* Results condition 2

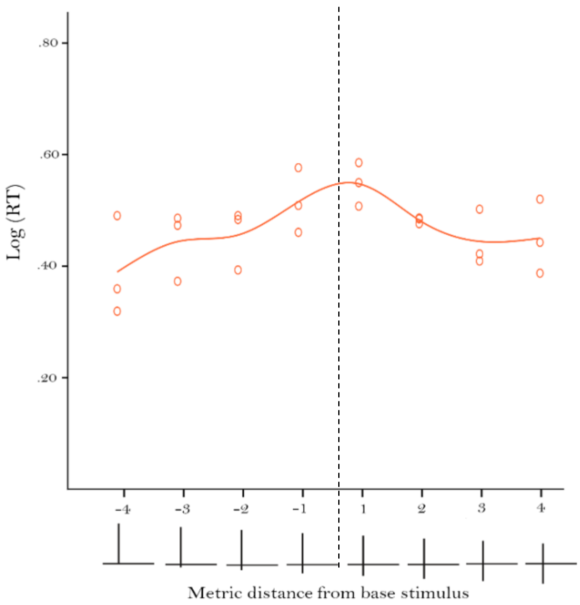


*Figure 10c.* Results for condition 3

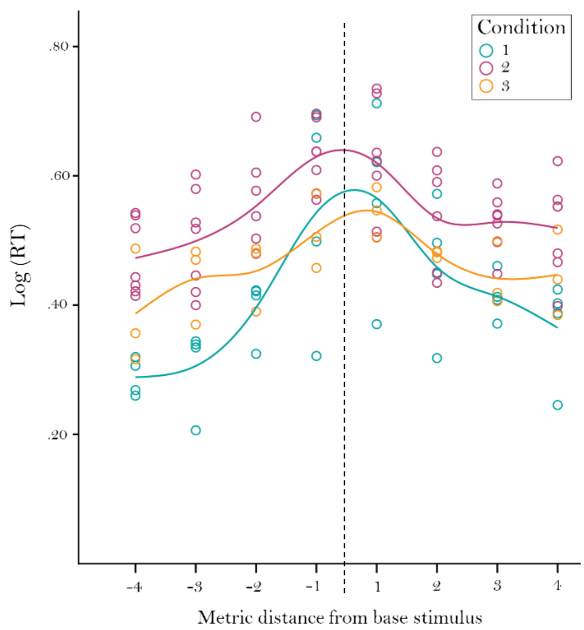


*Figure 10d.* Combined results

*Figure 10.* Medians of log transformed reaction times per participant.

Note. Reaction times were log transformed for each participant and the estimated trends were interpolated per condition. On the X-axis distances of the variants from the base stimulus in metric space are represented with the smallest changes in the center towards larger junction changes towards the extremes of the axis. Every step implies a change of 10° in angle or 1/18 of the length of one line segment.

## Study 2

In extension of our previous findings, we now wanted to investigate why we appear to be remarkably sensitive to alterations in junction type and whether we could find associations between low-level-information processing and viewpoint-invariant nonaccidental properties (Recognition-by-Components theory), such that a broader perspective could give rise to integrative theories considering perceptual regularities in the future. Hence, in our second study we investigated perceptual sensitivity to two-dimensional projected NAPs. In other words, this time three-dimensional information was translated to our two-line configurations in order to examine its impact on low-level visual processing.

### Methods

Experiments and analyses were coded in Python 2.7  using PsychoPy (Peirce, 2007; Peirce, 2009), psychopy_ext (Kubilius, 2013) and pandas packages. Full source code of the experiment automation is available at https://bitbucket.org/qbilius/twolines. R was used for performing repeated measures ANOVA and reported analyses were again manually validated with SPSS.

**Participants.** Ten master in psychology students  at the University of Leuven, participated in our second experiment (age: 21-23; males: 3, females: 7). Similar to the first study, participants had normal or corrected-to-normal vision. By contrast, participants were paid for their participation this time. The experiment was again performed individually and approval was obtained by the ethical committee of the Faculty of Psychology and Educational Sciences.

**Stimuli.** An analogous construction of stimuli to Experiment 1A was implemented in the sense that triplets were constructed with one base stimulus, one metric and one nonaccidental variant. However, this time our conditions were based on changes in junction type as a nonaccidental manipulation and other previously investigated nonaccidental features in geons (see Figures 11 and 12; Kim & Biederman, 2012; Amir, Biederman & Hayworth, 2012; for the entire stimulus set, see Figure 2 in Appendix B).

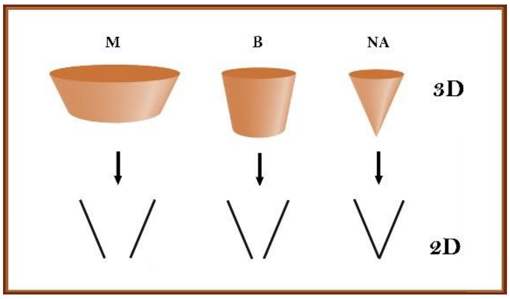


*Figure 11*. Example of translation of three-dimensional to two-dimensional NAPs.

Results of this selection could thus replicate the formerly encountered sensitivity to nonaccidental change in geons, but, which is more of our interest, could also demonstrate the origin of this sensitivity to lower level stimuli already. Finally, the modification in curvature in one line was included as well to verify a potential difference in effect of this manipulation in solely one line vs. in two lines (For the entire stimulus set, see Figure 2 in Appendix B).

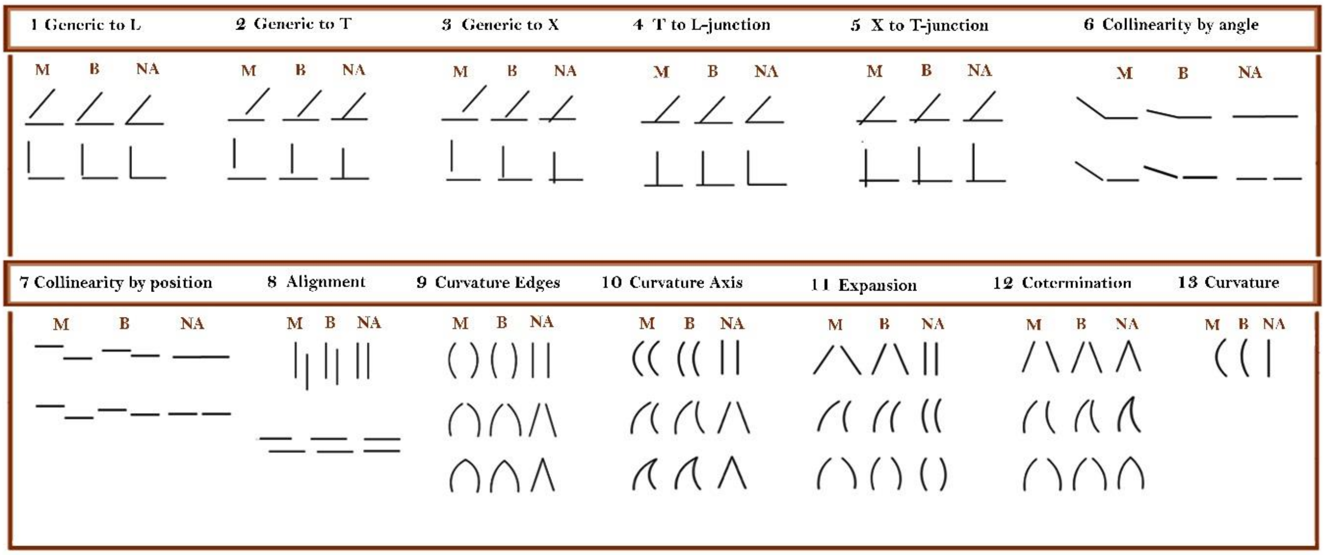


*Figure 12.* Stimulus conditions in Experiment 2.
Note. Distances were manipulated with 1/6 line length and curvature changed by dividing the radius by 2.

**Task.** The instructed task was similar to the one that was used in Study 1. Participants had to denote which one of the four quadrants comprised the different stimulus. All conditions were presented in a blocked manner, similar to the control experiment of Experiment 1A.

## Results

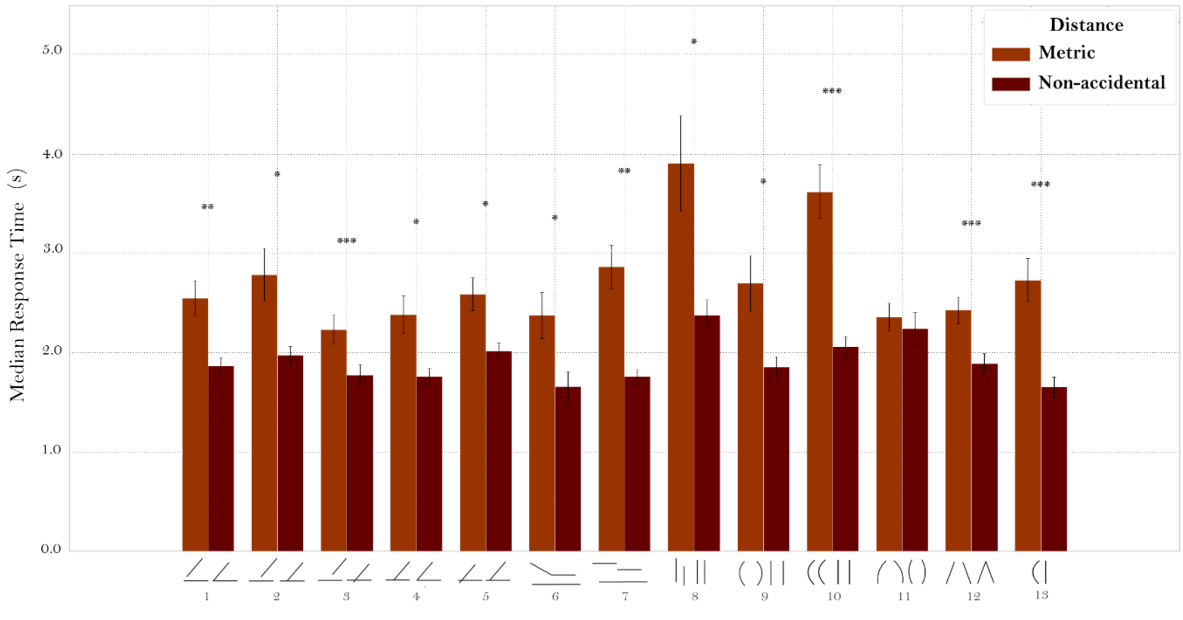


*Figure 13.* Average median response times per condition.
Note. Error bars denote standard errors of means across participants ($n$ = 9). * = $p$-value significant at α-level = .05, ** = $p$-value significant at α-level = .01, *** = $p$-value significant at α-level = .001 (after Bonferroni correction).

As shown in Figure 13, the expected nonaccidental effect was obtained for nearly all conditions after Bonferroni adjustment[7]. In other words, sensitivity to changes in junction type as well as to changes in collinearity, alignment, curvature and cotermination was found to be significant. More specifically, changes in junction type from generic constructions to coterminating (i.e. L and T) as well as to crossing junction types (X-junctions) resulted in significantly faster detection times (conditions 1, 2, 3, 4 and 5 with respectively $t(9) = 5.53$, $p < .001$; $t(9) = 4.20$, $p < .01$; $t(9) = 8.13$, $p < .001$; $t(9) = 4.65$, $p = .0012$; $t(9) = 4.10$, $p < .01$), which is comparable to the result of our cotermination condition 12 ($t(9) = 7.62$, $p < .001$). Furthermore, collinearity was detected faster than non-collinear variants too, when altered by angle as well as by position of two lines (conditions 6 and 7, with respectively $t(9) = 4.65$, $p = .0012$; $t(9) = 6.11$, $p < .001$). Next, metric transformations in alignment appeared much more difficult to distinguish from base stimulus than nonaccidental changes (condition 8, $t(9) = 3.98$, $p < .01$). Moreover, changes in curvature induced significant sensitivity levels in conditions 9, 10, 13 ($t(9) = 4.28$, $p < .01$; $t(9) = 8.69$, $p < .001$; $t(9) = 7.03$, $p < .001$, respectively). However, remarkably in contrast to the remaining conditions, no significant effect was finally found in the condition of Expansion (condition 11, $t(9) = 2.29$, $p < .05$, which did not survive Bonferroni correction; see 'Discussion').

We further asked if the observed effects for curvature in conditions 9 and 10 were due to configural sensitivity per se or resulted solely from participants' sensitivity to curvature in only one line. To address this question, we performed a repeated measures ANOVA. This analysis showed that the mean reaction time for condition 13 did not differ significantly from condition 9 ($F(1,9) = 1.62$, $p = 0.24$). Moreover, no evidence was found for significant differences in effect sizes of distance (NA vs. M) between both conditions ($F(1,9) = .001$, $p = .97$). In other words, a nonaccidental change in curvature for one line was perceived as quickly as a similar alteration in two lines simultaneously. By contrast, when considering reaction times in condition 10 vs. 13, significant discrepancies are to be noted. Reaction times were significantly higher for condition 10 ($M = 3.12$) than condition 13 ($M = 2.28$) ($F(1,9) = 26.09$, $p < .001$) and the effect of distance seems to be significantly stronger in condition 10 than condition 13 ($F(1,9) = 9.24$, $p = .014$). In sum, a nonaccidental change in curvature was detected significantly faster when modified in merely one line than when altering the stimulus axis curve, although this resulted in a stronger distance (NA vs. M) effect in the latter condition. These findings could therefore imply differences in configural advantages between conditions 9 and 10 (see 'Discussion'), which respectively did not vs. did show a strong NA-effect.

[7] After Bonferroni adjustment, critical *p*-values of .05, .01, .001 became $p = .05/12 = .0038$; $.01/12 = 7.69 \times 10^{-4}$; $.001/12 = 7.69 \times 10^{-5}$, respectively.

**Discussion**

In the two reported studies we investigated perceptual sensitivity to specific regular properties in two-line configurations. More in particular, we demonstrated significant sensitivity to perpendicularity and to position of intersections towards extremes (in case of non-orthogonal stimuli) in our first study, based on Feldman's Minimal Model Theory (2003). In addition, we also showed robust effects on sensitivity to changes in two-dimensional nonaccidental properties in general, based on the Recognition-by-Components Theory of Biederman (1987). At first glance, an early onset of encoding nonaccidental properties in the visual system thus seems a conceivable interpretation, given that the presented visual information was merely restricted to two lines. Still, some methodological choices and post-hoc interpretations of our findings need some further discussion.

**Design effects.** Primarily, we should explicitly mention the fact that the effects of our first study (i.e. on perpendicularity and position of intersection in non-orthogonal stimuli) were enhanced during the control experiment. This finding could possibly be assigned to the blocked paradigm that was implemented, whereas trials were randomly presented in the main experiment. In point of fact, this design increases the participants' experience in detecting one specific feature (similar to the follow-up Experiment 1B in this study, in which participants were exposed to exclusively one stimulus dimension), so that the task generally becomes easier. This effect of a blocked paradigm might also have played a role in the strong effects that we encountered in our second study. Given that blocking of trials thus provoked enhanced NA-effects, this might possibly be assigned to learning or mind set effects. By contrast, the random presentation of stimuli (in our main first experiment) could have caused interference between all reaction times, so that the threefold distinction between our subclasses of manipulations (angle size, position of intersection in non-orthogonal, in orthogonal stimuli) was less clear-cut for these results.

In short, the threefold distinction between conditions of our first study thus received the strongest empirical support in our control experiment. However, in this experiment an exceptional effect was also found for condition 10 (change in position of intersection in orthogonal X-junctions). Given that this effect was still relatively small, this finding could be rather coincidental. What is more, the selection of trials and, more conceivably, the collective setting might have had an influence on some results of our control experiment. Nevertheless, results of our follow-up experiment in Study 1 again indicated different sensitivities to the three gradual manipulations, even though participants only perceived manipulations of one of the three main subclasses.

Furthermore, we consistently used triplets instead of ranges of stimuli in our main studies, so that the step sizes of the manipulations were always selected a priori. In Study 1 & 2 we opted for 20 degrees in angle changes and 1/6 of the segment length for position changes (Experiment 1A). In Study 2 we used half radius curvature changes in addition to these parameter values. Although these changes seemed large enough to us given the stimulus sizes, it is possible that some effects were absent or smaller due to too small step sizes.

**Perception of viewpoint-dependent two-line features.** Before we discuss the main results of Study 1, notice that we consistently used the term ‘nonaccidental’ for the most regular variant per triplet throughout this paper. However, in Study 1 the regular properties cannot be defined as nonaccidental in its strict sense, but named them nonaccidental because a higher level of regularity was reached (according to the MMT). By constraining the degrees of freedom of the configuration, we assume that this configuration is perceived as less ‘coincidental’. These regular features can therefore be seen as nonaccidental, because there is only one orthogonal angle and only one midpoint in a (two-dimensional) metric space.

Apparently, the Minimal Model Theory could only account for sensitivity to perpendicularity, since null results and reversed effects were found for changes in intersection positions in respectively orthogonal and non-orthogonal stimuli. However, this threefold distinction in results is probably mostly due to the large variations in response times to the nonaccidental changes. As a matter of fact, metric changes in angle size and intersection positions did not seem to differ that much. Hence, we cannot conclude that changes in angle size are easier to detect than position changes (or vice versa).

Furthermore, we showed that perpendicularity was detected faster than differences between other angle sizes, while in Feldman’s investigation, orthogonality did not induce binding (Feldman, 2007). Given that he used the object-benefit-paradigm, in which participants implicitly react to grouping (because of a distracting task: comparison of points within or between line configurations), this methodological difference with our study should be taken into account. Apparently, although implicit grouping was not the case for orthogonal L-junctions according to Feldman’s findings, a faster detection was found in our paradigm, in which participants consciously have to perceive the configuration shapes. This suggests that orthogonal angle sizes are detected very quickly and are easily distinguished from other angle sizes, albeit this cannot be assigned to implicit configural effects. Hence, specialized sensitivity to orthogonal angles might already be present at low-level processing.

Additionally, we should notice that earlier research showed that sharp and obtuse angles could be over- and underestimated in L-junctions, respectively (Carpenter & Blakemore, 1973). In other words, sharp angles were perceived as larger than they actually were and for the obtuse angles the opposite was true. More specifically, the effect was strongest for the most sharp and most obtuse angles. This means that our metric variants (with the most sharp and obtuse angles) could have been perceived as more similar to the base stimulus, whereas the difference between the base stimulus and the nonaccidental variant stayed more or less the same. In case that this hypothesis is true, our NA-effect might have been enhanced by differently perceived metric changes.

With regard to changes in intersection positions, null results were obtained for orthogonal stimuli (T- and X-junctions) in our first study. Given the wealth of evidence on perceptual sensitivity to symmetry, this null result for midpoint intersections seemed fairly remarkable. However, we argued that this lack of effect could be assigned to perceived cotermination in the metric variant for these triplets. In this way, metric and nonaccidental variants of these triplets were possibly both seen as nonaccidental changes. Consequently, our visual system may detect midpoint intersections in orthogonal line-configurations as easily as coterminating configurations. Still, a similar sensitivity to the perceived coterminating (or metric) stimulus and the nonaccidental variant may also have been induced because of their equal number of symmetry-axes. As a matter of fact, if the metric stimulus was interpreted as coterminating (or L-junction), participants probably also perceived exactly one symmetry-axis in this stimulus (dividing the L-junction in two). As to explore whether sensitivity to metric variants indeed depended on perceived symmetry-axes, post-hoc analyses on groups of triplets within conditions 5 and 8 of Experiment 1A were performed. However, these analyses did not reveal significant differences between triplets with symmetric and asymmetric metric variants (see Figures 1 and 2 in Appendix D). So, the lack of effect should probably be attributed to perceived cotermination of this change indeed, rather than to perceived symmetry. To know whether changes in position towards midpoint intersections really need more effort to be detected, stimuli could be enlarged or changes in position could be reduced in future experiments, so that the metric variant (of T- and X-junctions) will certainly not be perceived as an L-junction.

In addition, our follow-up experiment in Study 1 (i.e. Experiment 1B) confirmed our results of Experiment 1A and demonstrated clear sensitivity to nonaccidental junction type changes. Yet, note that these interpretations were based on relative differences in slopes between the three conditions. So, based on the encountered NA-effect for angle change, the reversed effect for changes in intersection position in non-orthogonal stimuli and the lack of effect in orthogonal stimuli in Experiment 1A, we would anticipate respectively a convex-like trend, a concave-like trend and a stable linear trend. This indeed appeared the case for the latter two, but no convex curve was found for the change towards orthogonality. Since this condition did show the strongest increase and decrease in reaction times, reaction times for extreme variants probably reached a limit, so that the resulting curve was less convex due to this floor effect. In other words, we still believe that the earlier detection of metric variants in case of position changes should be attributed to perceived cotermination, which could better be explained by the RBC-theory (Biederman, 1987).

**Sensitivity to Nonaccidental properties in their classical sense.** With regard to our second study, we could claim that significant sensitivity arised for all junction type changes and other prototypical NAPs. However, this effect was absent for the NAP ‘expansion’, even though sensitivity to these changes were yet earlier shown with geon stimuli (Amir et al., 2011). Expansion may thus be processed differently from other 2D-translated nonaccidental properties or it is possible that the lack of effect in Expansion and position changes was partly due to too small metric changes. To clarify whether we are indeed only sensitive to expansion when presented in three-dimensional shapes or whether manipulations were not strong enough to induce the NA-effect, future experiments could include larger stimuli with different modification levels.

Finally, we encountered differences between changes in curvature. More specifically, the reaction times for curvature in both edges (condition 9) appeared to be comparable to curvature in only one line, whereas changes in curvature of the axis were distinguished more slowly (condition 10), which resulted in a stronger NA-effect. This clear difference in detection of the metric variant may either suggest an advantage of ‘symmetry’ (which was consistently present in condition 9) to perceive curvature changes, or, given that axis curvature changes do not lead to large changes in edge curvature, the objectively presented changes in curvature (i.e. of the edges) were smaller in condition 10. So, differences in reaction times to M-variants were possibly influenced by the amount of objective changes in curvature of the edges of the stimulus.

In conclusion, we thus assume that our visual system easily processes orthogonal angles and nonaccidental properties in two-line configurations. The fact that these two-dimensional projected NAPs were so easily distinguished, could imply that our visual system may either implicitly infer the nonaccidentalness from 3D and use top-down feedback mechanisms, or earlier areas are already involved in detection of nonaccidental features, so that information is rather accumulated in a feedforward manner (Hubel & Wiesel, 1962; Roelfsema et al., 1998; Stettler et al., 2002; Li et al., 2006). In this regard, Kubilius and colleagues (in preparation) also recently demonstrated lower activation of LO when perceiving stimuli with higher regularity levels based on the MMT, but there was no dependency of lower areas.

## Conclusion

In general, our two reported studies showed that both categories of regularity features (either based on 2D or on 3D) can provoke a strong perceptual grouping in two-line-configurations. In our investigation we obtained the strongest empirical support for perceptual grouping of orthogonal angles and nonaccidental properties. This study, together with previous research on sensitivity to 3D presented NAPs and orthogonal angles, suggests that the reported effects could probably be related to implicit higher order processing. Given that NAPs already induced a strong perceptual sensitivity in our two-line configurations, we assume that this investigation supports the importance of implicit three-dimensional assumptions, even when we perceive simple two-line-configurations.

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# Appendices

## Appendix A: Hierarchy of stimuli Study 1

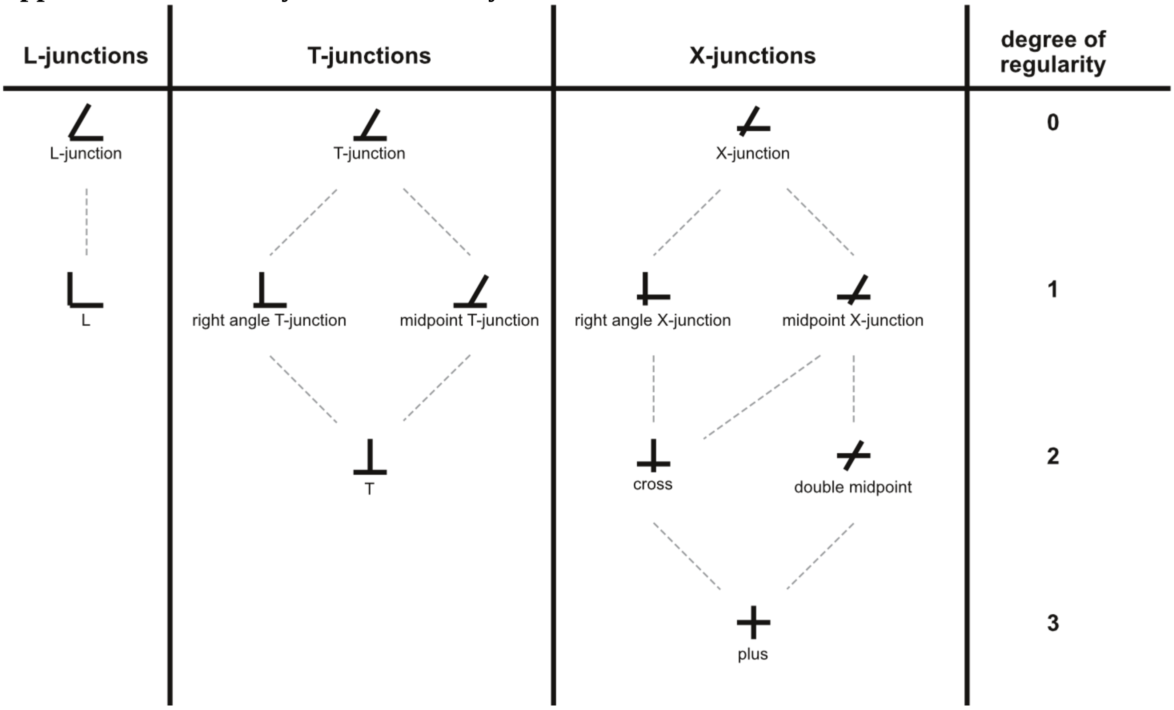


*Figure A1.* Hierarchy of our stimuli based on the Minimal Model Theory.

In Figure 1 a new hierarchy of two-line stimuli was proposed by Kubilius et al. (2013) based on the Minimal Model Theory. This theory states that each 'Genericity constraint' (i.e. decrease in degree of freedom, in this case, constraining angle size or intersection position) leads to one higher degree of regularity (Feldman, 2003; Feldman, 2007). Bearing this principle in mind, our stimuli are ordered from most generic cases (degree 0) up to the highest regularity level (degree 3 in this case). In our first study, sensitivity to differences in degree of regularity was therefore expected.

Notice that the twelve dotted lines in the above figure represent each of our twelve comparisons that were implemented in our experiment. The dotted line on the left, for instance, symbolizes our first condition of L-junctions in which angle size was manipulated (also see Figure 1 in Appendix B).

## Appendix B: Stimulus sets

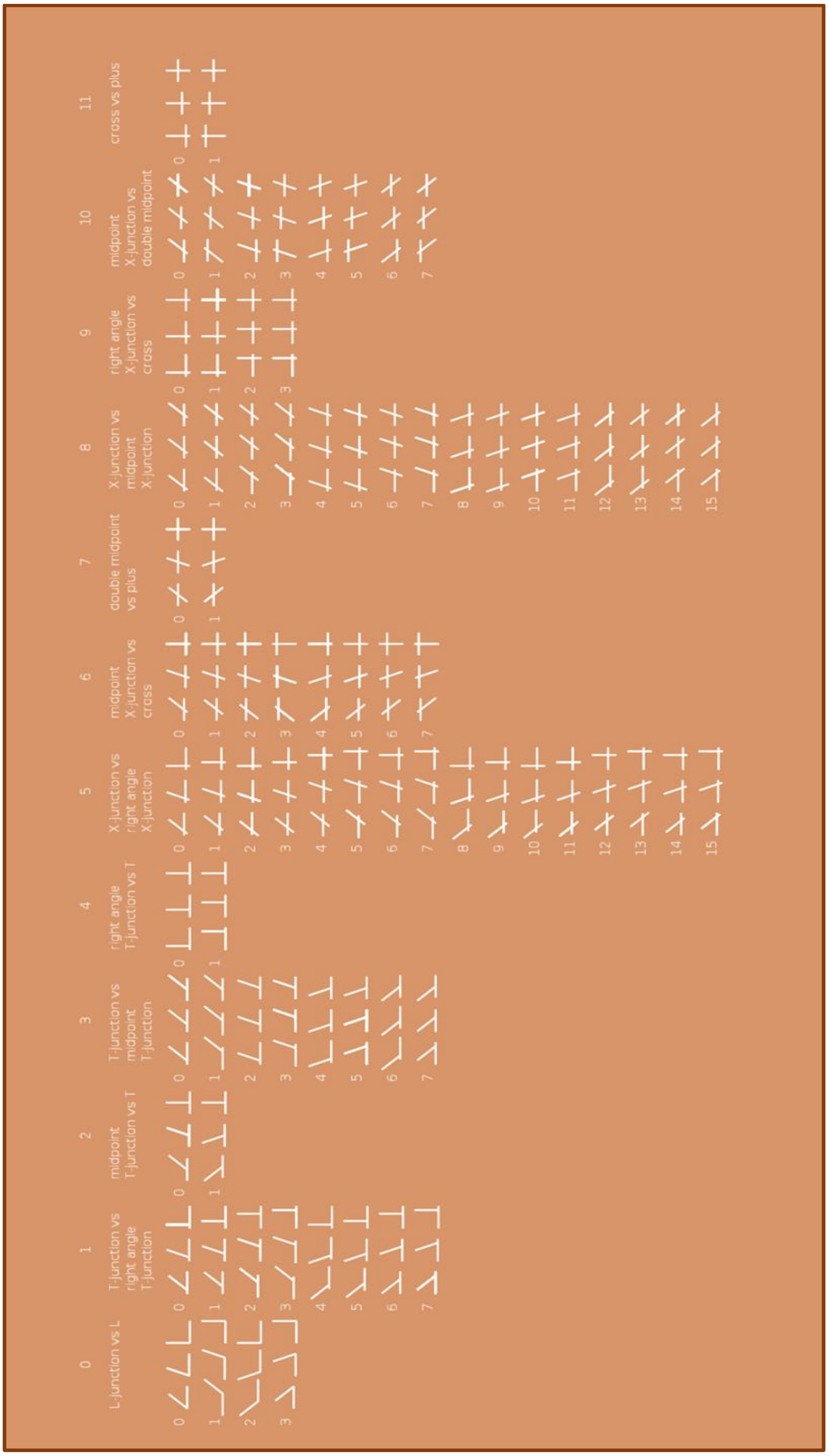


*Figure B1*. Stimulus set (Study 1).
Notice that conditions were numbered from 1 to 10 in the main text.

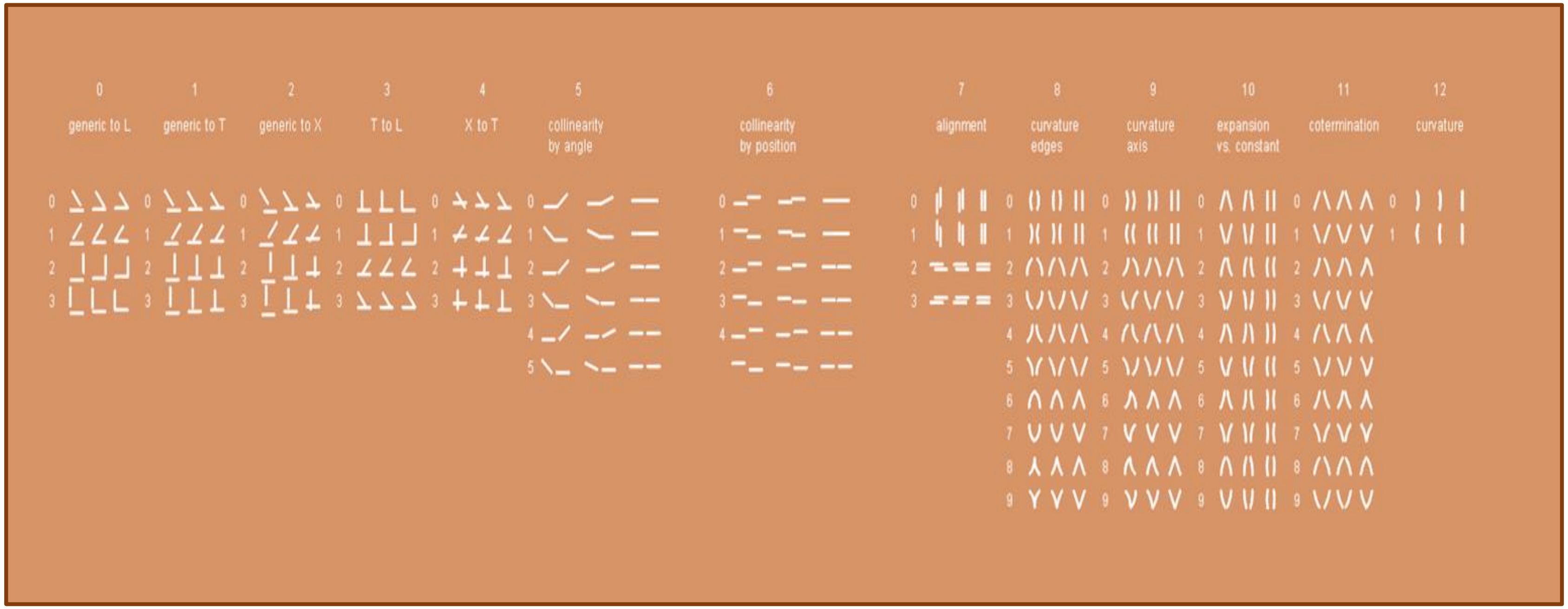


*Figure B2*. Stimulus set (Study 2).

Notice that conditions were numbered from 1 to 11 in the main text.

## Appendix C: Assumption checks

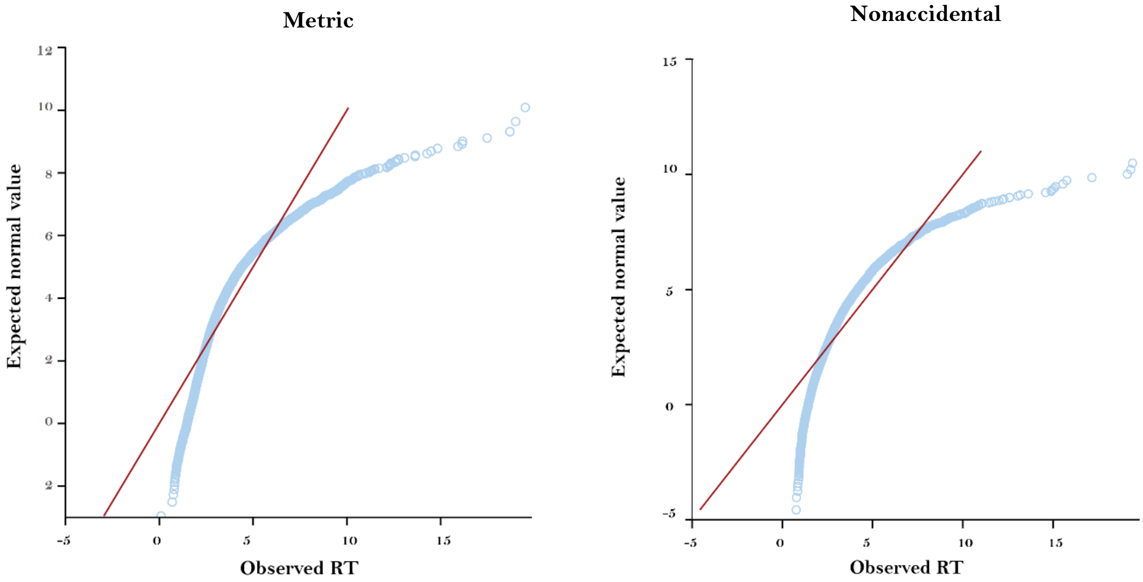


*Figure C1.* QQ-plots for reaction times in Experiment 1A (Study 1).
Note. The red line indicates the linear relationship that would be expected between the RTs and the values of a normal distribution, when the RTs would be precisely normally distributed. The blue dots indicate the actual relationship. From these graphs, the assumption of normality thus appears to be violated.

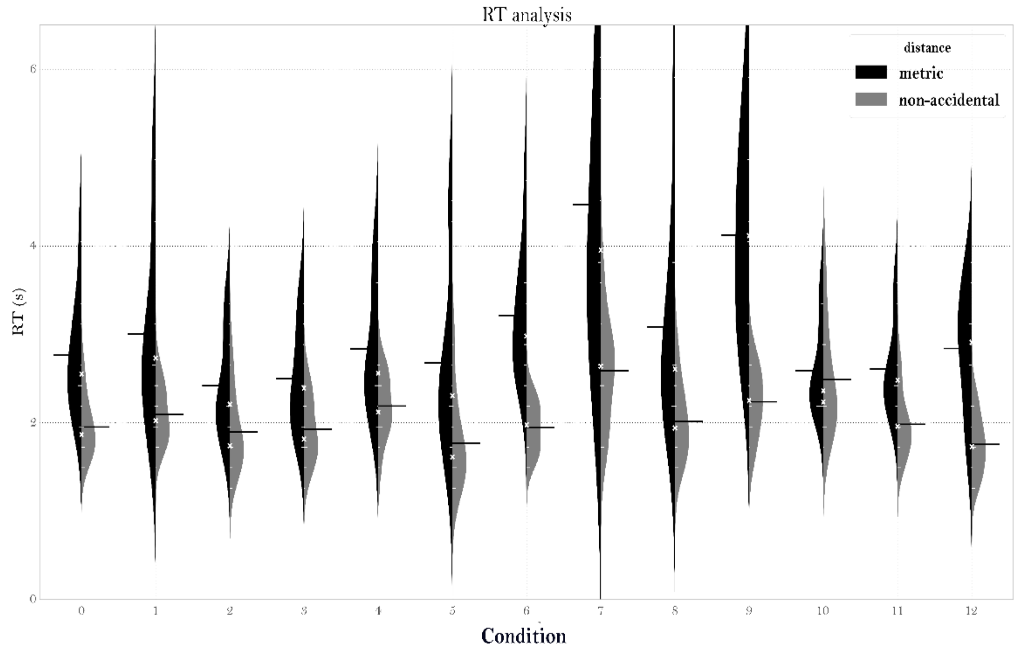


*Figure C2.* Bean plot for reaction times in Experiment 1A (Study 1).
Note. In this plot density curves of reaction times are depicted per condition. Most of these are not normally distributed, but skewed. Also notice that the distributions of RTs or the variances do not differ to a large extent between the metric vs. nonaccidental trials on average (when we would generalize for all metric conditions vs. all nonaccidental conditions).

## Appendix D: Symmetry in metric variants

Conditions 5 and 8 of the first main experiment included symmetric metric variants. Therefore bar plots were computed for distinctions between stimulus triplets within these conditions.

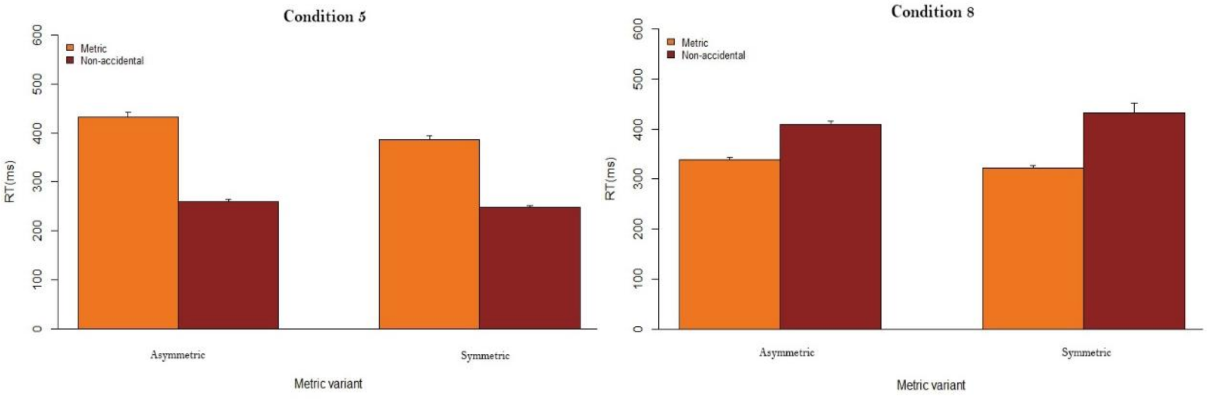


*Figure D1.* Response times for symmetric vs. non-symmetric metric variants (Experiment 1A).
Note. Response times are displayed for metric vs. nonaccidental changes in orange and brown, respectively. Within conditions 5 and 8, no differences are present for these RTs between triplets with an 'asymmetric' M variant and a 'symmetric' M variant.

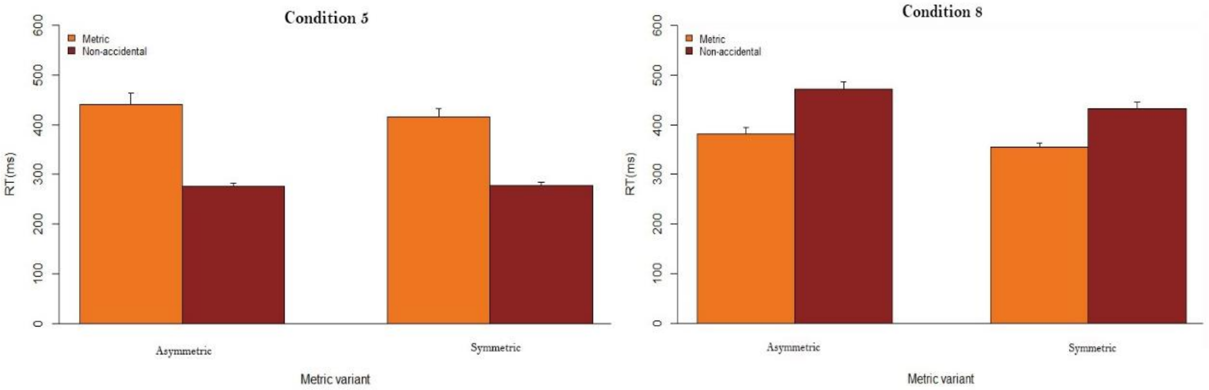


*Figure D2.* Response times for symmetric vs. non-symmetric metric variants (Experiment 1B).
Note. Response times are displayed for metric vs. nonaccidental changes. Again, no differences are to be noticed between triplets with an 'asymmetric' M variant and a 'symmetric' M variant.