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Precision of Visual Perception of Developing Fires

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Abstract: An aspect of human responses to fires is perceiving changes in intensity. The nature of fires can make this challenging, as flames and smoke are dynamic and change with time. For developing fires, this is in addition to growth occurring vertically and sometimes horizontally, with the footprint of the fire either remaining the same or increasing in size. The present study investigated how precisely humans could visually detect differences in the intensities and growth rates of simulated fires. Using a similar approach to research with non-symbolic visual quantities, a series of experiments compared the precision of judgments regarding which of two simulated fires was greater in intensity or growing faster in intensity when the footprint was fixed or varied. In addition, participants reported what characteristics they used to make their judgments. Precision was significantly worse when comparing the growth rates versus the intensities of fires, and it was better when the fire footprint varied. This provides initial estimates of the precision of mental representations of fire intensity and growth. In addition, participants reported using multiple characteristics, including the size of flames and smoke produced. The present study indicates that humans can precisely detect differences in the intensities of fires using visual cues, but have difficulty when comparing growth rates. We discuss how this suggests that the growth rate may not be a reliable visual cue used by occupants when responding to fires.

Keywords: flames; smoke; fire safety; perception; decision making; quantitative cognition; egress

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1. Precision of Visual Perception of Developing Fires

Room fires can develop quickly, increasing in intensity after ignition to spread through the rest of the building. A key component to occupant safety during fire incidents is when they decide to take protective action, such as evacuation. During the initial growth stages, multiple perceptual cues from the fire are available to occupants. This includes smoke alarm sounds, smoke odors, as well as visual indicators such as smoke thickness. An action frequently reported by occupants in post-incident interviews is investigating the source of said cues to determine if there is a true fire threat; this often leads to them viewing flames [1]. In these situations, visual cues about the intensity and growth rate of the fire are available from the visual smoke and flame characteristics. Although such cues are reported as being used to estimate the risk posed by fires [2], how well individuals can detect changes in visual fire characteristics remains to be investigated. To be used as indicators of the risk posed by the fire, these visual cues need to be perceptible to humans. The present study investigated the precision at which individuals could detect differences in the visual cues of fire intensity and growth.

1.1. Role of Perception in Fire Safety Egress Models

Hazard perception is the incipient step for taking protective action in models of human behavior during fire incidents. A key objective of fire safety science is designing structures to provide enough time for occupants to take protective action once a fire has ignited. Crucial to this is predicting human responses to fires to calculate the required safe egress time (RSET) [3]. Building designs use the RSET to construct and select materials to provide an available safe egress time (ASET) that is greater than the RSET, thereby providing a safety margin for occupants to take protective action. The estimates of the RSET tend to separate the movement time—how long it takes an occupant to move to a building exit after deciding to escape—from the pre-movement time—how much time elapses between the fire ignition and the decision to escape.

Reviews of human behavior in fire research have identified that, while a large focus has been on post-movement time, pre-movement time plays a critical role in determining the RSET, and the predictive factors are not as well understood [3]. This includes sensing fire hazard cues and perceiving them as indicative of a fire emergency. The protective action decision model (PADM) [4] has been applied to fire emergencies to predict pre-movement decision making, with the first phase focusing on the initial perception of fire cues, smells, sounds, and sights. Interviews after residential fire incidents have provided evidence that the initial actions that occupants took were influenced by the characteristics of these cues, such as the thickness of the smoke [1]. This suggests that perceptible variations in these cues influence occupant responses.

A challenge posed to occupants is identifying whether such cues are indicative of a fire actually being present or a false alarm. During true emergencies, such ambiguity contributes to occupants further investigating the source of cues, often by moving through smoke to visually observe flames [5]. When fires are in the incipient stage, they are still growing in intensity. While some fires may decrease on their own due to a lack of fuel, a growing fire continues up to flashover, where the fire transitions from burning in a specific location to engulfing all consumables within a space [6]. While the fire is developing, multiple visual cues are available regarding the intensity of the fire, as well as how quickly it is growing. Although research indicates that occupants can make use of visual cues to infer the risk posed by fires, it remains unclear how precisely they can detect the differences in said cues. Based on non-symbolic quantity perception research [7], there may be individual differences when perceiving fire cues that contribute to some visual indicators of fire severity being below perceptible levels for some individuals.

1.2. Observer Perceptions of Developing Fires

Multiple visual cues can indicate the intensity and growth rate of a fire. The heat release rate (HRR) of a fire corresponds to the rate of heat production by a fire. The HRR is a critical indicator of the level of danger posed by a fire to occupants [8]. With other factors remaining consistent, room fires with greater peak HRRs reach unsafe temperatures and carbon monoxide levels for occupants in shorter amounts of time. The growth of developing fires can be profiled using changes in the HRR and associated visual characteristics. By using temperature sensors in controlled settings, the profiles of HRRs over time have been used to identify different phases of fire development and to estimate the typical patterns of the growth before flashover. Fire growth is defined as the period of time between fire ignition and the maximum, or peak, HRR value. Calorimeter measurements for different materials have been used to characterize growth via an exponential function, referred to as a t^2 curve with an instantaneous HRR defined as $HRR = \alpha\ (t^2)$; the α coefficient indicates the rate of growth (kW/s^2), and t indicates the elapsed time (s) after ignition [6]. With a variety of materials exhibiting different growth rates, α coefficients have been estimated to correspond to fire growth that is slow, medium, fast, and ultra-fast, which are used in performance-based models of building design for fire safety [9]. Multiple visual characteristics of fires can be estimated at different points in growth using the HRR. For example, along with the diameter of the fire base, the HRR is used to estimate the height of the flames and the pulsation rate of the fire plume puffs [10]. This indicates that the intensity and rate of the fire growth, associated with HRR, can be estimated using visual features of fires.

Developing fires in buildings can be broadly categorized as having a fixed versus varied footprint. Fires that are footprint-fixed (e.g., a fire in a trash can) increase in HRR by spreading vertically with a constant base. Fires that are footprint-unbounded, or varied, (e.g., a fire on a carpet) increase in HRR by spreading vertically and horizontally with an increasing base. Increases in the HRR for both categories of fires follow a t^2 function, with the spread rate of varied footprint fires being used to calculate the α coefficient [11]. Visually, this leads to differences in the characteristics that can be used to estimate the rate of growth. Specifically, for varied footprint fires, the width of the base indicates the fire intensity, along with other visual characteristics.

With the availability of multiple visual characteristics associated with fire severity, initial investigations have been conducted with observer perceptions of fires. These investigations have predominantly focused on fixed footprint fires during the growth phase. Multiple experiments indicate that human observers are biased in their judgments of the rate of growth and the intensity of fires displayed via images. When presented with two photographs of room fires at different points in development, participants tended to underestimate the growth rate, therein reporting that the fire would take longer to reach the larger size than in actuality [12]. Furthermore, the direction of bias in estimates of growth rate was observed to vary by the point in fire development, with overestimation near ignition and, later, underestimation [13]. Judgments of the visual characteristics associated with intensity can also be inaccurate. For example, Hulse and colleagues (2020) observed that participants displayed lower accuracy with larger fires when selecting which of a set of images depicted the size of the flames and the volume of smoke displayed immediately prior when viewing a brief video of a kitchen fire [14]. This research suggests that the judgments of fire intensity based on visual characteristics may be imprecise. However, the extent to which the precision of judgments regarding fire intensity varies by fixed versus varied footprint fires, as well as the types of visual characteristics participants use in their decisions, remains to be investigated.

1.3. Non-Symbolic Quantity Perception

Approaches used in non-symbolic quantity perception are well suited to estimate how precisely individuals can perceive the differences in fire characteristics. When used in cognition and perception research, these approaches systematically present non-symbolic images that manipulate the value of a quantity (e.g., dot arrays to manipulate number, circles to manipulate size) and measure the performance of the individuals asked to judge said stimuli. By doing so, researchers can investigate how changing characteristics of the stimuli (e.g., shape and color) affect how well people can perceive non-symbolic quantities across a variety of conditions. This makes the approach well-suited for investigating how manipulating the characteristics of fires affects how precisely individuals can perceive differences in fires.

When asked to judge which of two visual non-symbolic quantities is greater in value, without counting or measuring, ratio effects are observed during performance. Specifically, the ratio effect refers to higher accuracy, thus responding correctly, when the proportional difference between the two values is larger. For example, accuracy tends to be higher when judging which set of dots is greater in number (without counting) with 24 versus 12 dots (24 divided by 12 is a 2.00 ratio) compared to 20 versus 18 dots (20 divided by 18 is a 1.11 ratio). The effect is argued to be the result of the level of noise in the corresponding mental representations of quantities that are modeled as Gaussian distributions [15]. When arranged on a more-versus-less continuum, the closer two representations of non-symbolic quantities are in value, the more likely they are to overlap, thus contributing to worse performance during ordinal judgment tasks [16]. Ratio effects have been observed using multiple non-symbolic visual quantities, including number, size, length, and density [7,17,18]. Differences have been observed across non-symbolic quantities, characterized using Weber fractions (w) which indicate the level of noise in corresponding mental representations [15]. Smaller w values closer to zero indicate less noise in the mental representations, thereby allowing for more precision at detecting smaller differences between quantities. For example, more precise w values have been observed when comparing the sizes (w = 0.08) and lengths

(w = 0.05) of individual objects versus the number (w = 0.17) and spatial density (w = 0.30) of objects in arrays [18]. The precision of visual fire intensity judgments has yet to be investigated.

1.4. Visual Perception of Dynamic Objects

Whereas the precision of non-symbolic quantity comparisons has been estimated with static quantities, fires are dynamic, and their corresponding visual characteristics change with time. Even with fires that are relatively stable in their HRRs over time, the variations in the flow of fuel and the fluid dynamics of the available oxygen, among other factors, contribute to temporal changes in the heat released, along with the corresponding visual cues. As such, it is unclear how precisely observers can detect the differences in fire intensity using dynamic visual characteristics. Prior research investigating observer sensitivity to the acceleration of visual objects offers some insight. Similar to the HRR in models of fire growth, the location of accelerating visual objects is non-linear with time. Studies have observed that individuals are poor at detecting the acceleration of visual objects compared to derivatives, velocity, and location. For example, participants could detect smaller differences in the velocity compared to the acceleration of visual dots moving linearly [19]. Evidence that acceleration detection can vary by type of movement has also been observed. Specifically, the threshold for detecting acceleration compared to a constant velocity standard was lower for radially versus horizontally moving objects [20]. When applied to fires, this suggests that individuals may be more precise when comparing the intensities of stable HRR fires, compared to the growth rates of fires, and this may differ for footprint-fixed versus varying fires.

1.5. The Present Study

We investigated how precisely individuals could detect differences in developing fires and the visual characteristics they reported attending to when doing so. Across three experiments, participants were presented with simulated fires of varying intensities and growth rates to compare and judge (see Table 1). The fires were numerically simulated using FDS [21] and visually rendered using PyroSim [22]. Simulations were used for two reasons. First, they allowed for greater control over the characteristics of the fires, including the intensities and combustion properties. Second, numerical simulations have been used in multiple jurisdictions for assessing the life safety systems of buildings [9]. Similar to non-symbolic magnitude research, the precision of fire perception was assessed using a comparison task where two fires were simultaneously presented, and the ratio difference between them systematically varied. The ratios varied from smaller (e.g., number: 10 dots versus 9 dots = 10/9 = 1.11 ratio) to larger (e.g., number: 24 dots versus 12 dots = 24/12 = 2.00 ratio), and the accuracy of responses was recorded. The precision of the corresponding mental representations was calculated as a Weber fraction using the accuracy at each ratio via a Bayesian framework [23]. Using Weber fractions, we investigated how fixing or varying the footprint affected the perception of fire intensity. Participant self-reports of what information they used to make their judgments were used to investigate what types of visual cues were used to support their fire intensity judgments.

Table 1. Overview of experiment designs, including the type of comparison and included fire footprint conditions.

Experiment	Fire Comparison	Footprint Conditions
1	Intensity (*HRR*)	Fixed Varied
2	Growth (t^2 curve)	Fixed Varied
3	Growth (linear curve)	Fixed

2. Experiment 1

The objective of Experiment 1 was to assess how precisely individuals could detect differences in fire intensity when the footprint of the fire was fixed or varied, as well as what cues they reported using when doing so. Based on prior non-symbolic quantity research, it was hypothesized that performance would be higher with greater ratio differences in HRR. Second, it was hypothesized that performance would be higher in the varied footprint condition based on evidence that multiple congruent cues can improve quantity discrimination accuracy [24]. Using simulated fires, participants viewed video clips and then judged which fire was more intense, followed by reporting what information they used to base their judgments.

2.1. Methods

2.1.1. Participants

A total of 60 participants, recruited from the online participant panel Prolific, completed the study, hosted online via the Qualtrics XM platform. Participants varied in age (M = 36.23, SD = 14.12, Min = 19, Max = 71), biological sex (N Female = 30, N Male = 30), and race (N White = 46, N Black or African American = 7, N Asian = 4, N American Indian or Alaska Native = 1, N multiple = 2). Participants were asked to self-report any fire-related profession experience they possessed (volunteer firefighter; tradesman that works with fire, e.g., welder; chimney technician; fire protection engineer; forestry technician). A total of four participants reported having fire-related professional experience. In addition, participants were asked if they had encountered any adverse fire events ("How many times have you...": "Had to evacuate your home due to a wildfire."; "Used a fire extinguisher to put out a fire in your home, work, or school (not including practice drills)."; "Had a fire emergency at your home."; "Had a fire emergency at your work or school (not including fire drills)."; "Had a wildfire warning issued that included your home, school, or office."; "Had your home, school, or office threatened by a wildfire."; "Had your home, school, or office damaged or destroyed by a wildfire."; "Had your home, school, or office damaged or destroyed by a fire that started inside the building or a next-door building."). A total of 33 participants reported experiencing at least one adverse fire event. For completing the study, participants were provided with a 5 USD monetary incentive (taking approximately 25 min to complete the study). For all experiments, participants gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Institutional Review Board of Morgan State University (#20/10-131).

2.1.2. Materials

Participants were presented with multiple video clips displaying simulated fires. The videos were hosted online via the Vimeo platform and displayed without video controls. At the start and end of each video was an inter-stimulus interval of 500 ms, during which a brown rectangle was rendered. The simulated fires for each video were displayed for 8 s. Pilot testing indicated that this video duration was long enough for participants to respond accurately for large ratios and short enough to complete the task within the experiment session.

Numerical simulations of fires were generated with Fire Dynamics Simulator (FDS; version 6) software and visually rendered using PyroSim (version 2021; Thunderhead Engineering) to display fires burning at different intensities. The FDS software uses a large-eddy-based approach to approximate the fluid dynamics and thermal properties of real fires. To create simulations for videos, a square-shaped burner centered on the bottom of a three-dimensional space emitted a specific heat release rate per unit area (HRRPUA) simulating propane being burned (carbon monoxide yield = 0.005, soot yield = 0.024). With the exception of the back wall, floor, and ceiling, the simulation environment was open and had a resolution of 5 cm cubic voxels, and combustion metrics were calculated for each voxel in 0.033 s increments, corresponding to 30 frames per second. The size of the environment and burner varied with the footprint condition. For the fixed footprint condition, the environment was 4 m wide, 4 m deep, and 8 m high, and the burner was 1 m for each side. For the varied footprint condition, the environment was 8 m wide, 8 m deep, and 4 m high, with the burner size varying from 0.4 m to 7.2 m per side.

Visualizations were rendered as two-dimensional with an orthographic environment camera positioned in front of the environment such that it was centered vertically and horizontally with a gray background. The cutoff for displaying voxels as flames versus smoke was set at 200 kW. The visualization settings used to display flames were such that lower and higher HRRs corresponded to colors closer to deep red versus near-white. Smoke was rendered such that darker, more opaque colors indicated sootier smoke. The software approximated visual flames and smoke by comparing the HRRs of adjacent voxels and smoothing over values to generate curved and near transparent edges. Images for each simulation frame were rendered at a resolution of 600 by 400 pixels (height and width for fixed footprint; width and height for varied footprint).

To generate pairs of videos that varied in fire intensity, the HRRPUA and burner widths were varied (Figure 1). When all other parameters are kept the same, burners of the same width that have different HRRPUA values, and those with the same HRRPUA and different widths generate fires of different heights. For the fixed footprint condition, selected HRRPUA values (rounded to nearest integer) ranged from 130 to 1560 kW/m^2. Each video pair contained the same burner width and varied in HRRPUA value. For the varied footprint condition, selected HRRPUA values (rounded to nearest integer) ranged from 280 to 571 kW/m^2, and selected burner widths ranged from 0.4 m to 7.2 m. Each video pair contained the same HRRPUA and varied in burner width. Simulations for each pair were rendered horizontally side-by-side in each video (1340 by 820 pixels). All materials are available via an Open Science Framework online repository (https://doi.org/10.17605/OSF.IO/F35TU (accessed on 10 August 2023)).

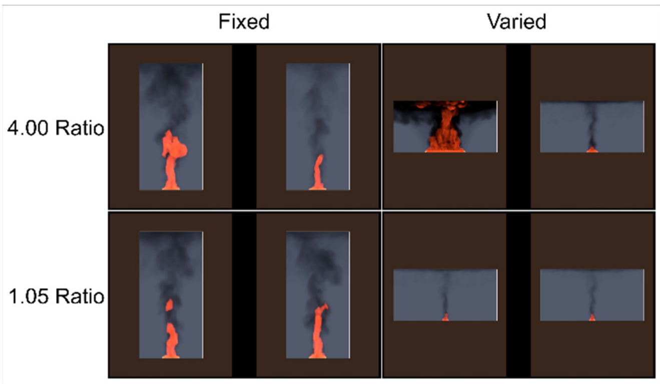

Figure 1. Example screenshots from videos generated from simulations for the comparison task. Participants viewed and judged videos of side-by-side fire simulations. HRR was manipulated in the fixed condition (left column) by the amount of heat released over the footprint area and in the varied condition (right column) additionally by the width of the footprint. For Experiment 1, fires varied in HRR by a ratio (larger value divided by smaller value), with smaller ratios (bottom row) being closer in value than larger ratios (top row).

2.1.3. Procedure

All study tasks were hosted and presented online via the Qualtrics XM platform. Participants from the online panel Prolific.co were recruited by posting a study ad to the online platform. Participants were pre-screened by requiring the use of a laptop or desktop computer to complete the study, having normal or corrected-to-normal vision, and to be fluent in English. Those that consented to participate in the study were then presented with the task. Instructions emphasized that the videos were simulations of real fires and that participants would judge which fire was more intense. Participants were first provided with practice trials with a large difference (12:1 ratio) and provided corrective feedback. Each trial began with the participant pressing a 'start' button. The participant was then instructed to watch the video (automatically loaded and played), which contained fires on the left and right side of the screen. The video was then removed, and the participant was prompted to indicate whether the left or right fire was more intense. After completing practice trials (practice ratio, 12:1), participants were presented with test trials. Response accuracy feedback was provided to encourage participants to attend to fire intensity cues. The order of test trials was randomized across participants. Once test trials were completed, participants were prompted to indicate the information that they used to judge which fire was more intense. They were then asked to report demographic information and were provided with a debriefing statement.

2.1.4. Design

During the comparison task, participants were assigned to a footprint condition (two-levels: fixed and varied, manipulated between subjects). In the fixed condition, the width of the fires remained constant with the HRRPUA varying. For each video, the difference in intensity between each fire was defined using HRR. In the varied condition, the width of the fires and HRRPUA were varied. Similar to the fixed footprint condition, the difference in intensity was defined using HRR. However, the difference in width of the burners also varied by the same ratio as the HRR. For both conditions, the ratio difference in fire intensity was systematically varied from small to large (ratios: 1.05, 1.11, 1.20, 1.50, 2.00, 4.00, manipulated within subjects). These ratios were selected from prior approximate magnitude research with non-symbolic number and area [18]. The order of ratios was randomly selected across participants, with eight trials per ratio (side with more intense fire counterbalanced across trials).

2.2. Results

Two indicators of performance were computed as dependent variables. The accuracy was calculated by marking whether the participants selected the fire that was greater in intensity (1 = correct; 0 = incorrect). The accuracy for each ratio was used to calculate the precision of the corresponding mental representation using Weber fractions [16]. For each participant, the Weber fraction, w, was estimated using a Bayesian approach to fit the probability of a correct response as the intensity ratio increased [23]. The resulting w was used to compare the precision of the responses across conditions, with smaller values indicating greater precision.

A mixed methods approach was used to identify the characteristics that participants reported using to make their judgments about fire intensity. The same coding scheme was used for all experiments in the present study. Using prior research on occupant accounts of residential fires [1] as well as the visual characteristics rendered by PyroSim, a coding scheme was developed to identify whether participants specifically referred to flames and smoke (cue type: flame, smoke) or the fire without these specific cues (cue type: fire). A second category of dimension (dimension: height, width, size, color, puffing) indicated whether the responses referred to a quantity of the cue, specifically height (the vertical extent of the cue), width (the horizontal extent of the cue), more generally regarding the overall size of the fire (size), color (the hue or brightness of the cue), and the extent of puffing (how much the cue pulsated or puffed). Using the Taguette platform, two trained research assistants, who were naïve to the hypotheses of the study, coded the participant responses across all experiments in the present research; no distinction was made between experiments. The responses could have multiple codes depending on the number of characteristics identified. After coding, each participant was scored to indicate which cues (fire, flame, or smoke) by dimension (size, height, width, color, puffing) cells were present (1) or absent (0) in their comments.

All analyses were conducted using R and the following packages: 'lme4' [25], 'lmerTest' [26], 'effectsize' [27], 'multcomp' [28], 'emmeans' [29], and 'ggplot2' [30]. The statistical tests were two-tailed (alpha = 0.05), and multiple comparison tests were adjusted using either Sidak or Holm corrections. Satterthwaite's method was used to estimate the degrees of freedom for the linear mixed models.

2.2.1. Performance

Binomial tests indicated that the performance was significantly above chance for all the ratio and footprint conditions ($ps < 0.001$; see Supplementary Material). A mixed model logistic regression predicting a correct response (random intercept for participant) yielded significant main effects of ratio (scaled and centered), coefficient = 3.24 (SE = 1.17), z = 2.76, p = 0.006, OR = 25.48, footprint (varied as the baseline), coefficient = 1.80 (SE = 0.83), z = 2.17, p = 0.030, OR = 0.17, and no significant interaction, coefficient = 0.18 (SE =1.28), z = 0.14, p = 0.887, OR = 0.83 (intercept: coefficient = 5.59, SE = 0.76, z = 7.32; Figure 2). Accuracy was significantly higher for larger ratios, and it varied compared to the fixed footprint condition.

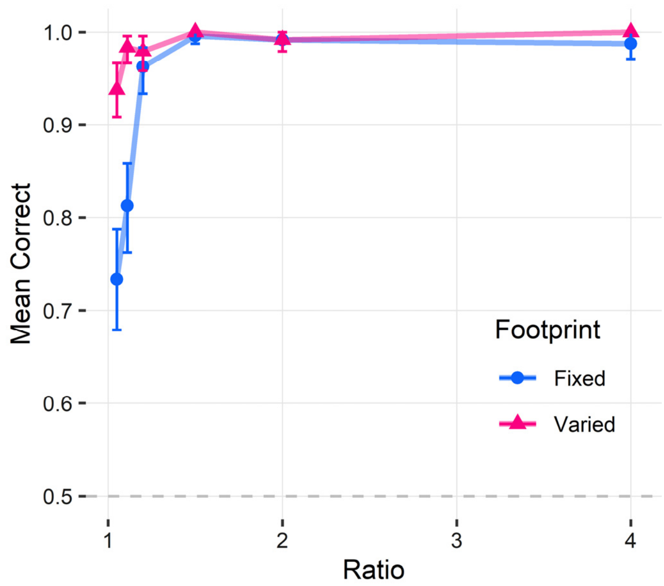

Figure 2. Mean proportion of correct responses in the comparison task for Experiment 1 for each ratio (larger intensity divided by smaller intensity) and footprint condition. Error bars indicate 95% confidence intervals.

2.2.2. Weber Fraction

A Mann–Whitney test indicated that precision was greater for the varied (M = 0.03, SD = 0.05, nearest fraction = 103/100) than for the fixed footprint condition (M = 0.09, SD = 0.08, nearest fraction = 109/100); W = 779, p < 0.001.

2.2.3. Qualitative Analysis

All but one participant (fixed footprint condition) provided text responses about the use of fire characteristics during the task (Figure 3). Significantly more than a single category was identified in the participant responses in both footprint conditions for cue type (fire, flame, or smoke; one-sample Wilcox test; fixed, V = 220, p < 0.001; varied, V = 231, p < 0.001) and dimension (size, height, width, color, or puffing; fixed, V = 246, p < 0.001; varied, V = 153, p < 0.001). Mixed model logistic regressions (binomial link) were fitted to predict whether a comment category was present (random intercept for the participant) and included main and interaction effects of footprint and characteristic (the cue type and dimension; separate models for each). For cue type, a significant interaction with footprint condition, χ^2 (2) = 11.86, p = 0.003, was observed (the significant main effects of the footprint and cue type; ps < 0.05; see the Supplementary Material for descriptive statistics). Post hoc tests indicated that the cue type interaction was driven by comments in the fixed condition mentioning flames more often than fire, $z = 3.47$, adj. $p = 0.005$, and smoke more often than fire, $z = 3.47$, adj. $p = 0.005$, with fire being mentioned more often in the varied than in the fixed condition, $z = 3.02$, adj. $p = 0.022$. For dimension, a significant interaction with footprint condition, χ^2 (4) = 21.34, $p < 0.001$, was observed (the significant main effect of dimension; $p < 0.05$; see the Supplementary Material for descriptive statistics). The dimension interaction was driven by comments mentioning height more often in the fixed than in the varied condition, $z = 3.61$, adj. $p = 0.007$, height and size more often than width, puffing, or color in the fixed condition (adj. ps < 0.05), and size more often than color, height, or puffing, as well as width more often than puffing in the varied condition (adj. ps < 0.05).

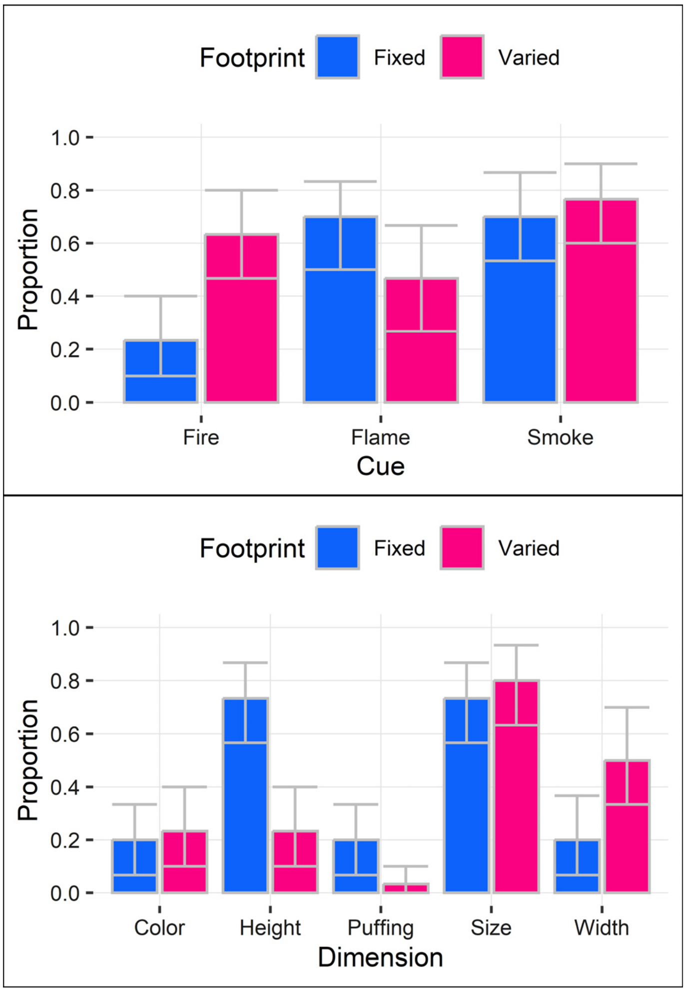

Figure 3. The proportion of participants whose comments contained each category of cue type (top panel) and dimension (bottom panel) by footprint condition in Experiment 1. Error bars indicate 95% confidence intervals.

Summary: The responses indicated that participants attended to multiple visual characteristics and their corresponding dimensions. The flames and the height of the fires were more frequently attended to in the fixed footprint condition and the size of the fires in the varied footprint condition.

2.3. Discussion

The results of Experiment 1 indicated that the participants were sensitive to differences in fire intensity, and this varied with respect to fire footprint condition. In both footprint conditions, the participant responses were significantly affected by the intensity ratio. The presence of a ratio effect extends prior research by providing evidence of approximate magnitudes with fire intensity. However, the Weber fractions were smaller for the varied footprint condition, thus indicating that the corresponding mental representations of fire intensity were more precise compared to the fixed condition. Participants reported attending to multiple visual cues when making their judgments, wherein they more frequently reported using the height of the flames in the fixed footprint condition and general size in the varied footprint condition. Overall, Experiment 1 suggests that individuals can precisely represent the intensity of visually represented fires.

3. Experiment 2

The goal of Experiment 2 was to determine how precisely individuals could detect differences in the growth rates of fires. Experiment 1 indicated that individuals could detect small differences in the stable intensities of fires. To determine how well individuals could detect changes in developing fires, a new set of videos were created to simulate fires that increased in intensity following a t^2 curve. Similar to Experiment 1, two types of fire growth were investigated: fixed footprint fires, which increased in the HRRPUA with the same area, and varied footprint fires, which increased in area with the same HRRPUA. During the comparison task, participants were asked to judge which fire was growing faster. We hypothesized that individuals would be able to detect which fire was growing faster with greater precision in the varied footprint condition.

3.1. Methods

3.1.1. Participants

A new sample of 60 participants was recruited from the online participant panel Prolific and completed the study, hosted online via the Qualtrics XM platform. Participants varied in age (M = 34.20, SD = 11.15, Min = 20, Max = 66), biological sex (N Female = 29, N Male = 31), and race (N White = 48, N Asian = 2, N American Indian or Alaska Native = 2, N Black or African American = 5, N multiple = 3). A total of two participants reported having fire-related professional experience, and 22 participants reported experiencing at least one adverse fire event. For completing the study, participants were provided with a 5 USD monetary incentive (taking approximately 25 min to complete the study).

3.1.2. Materials

A new set of videos displaying pairs of fires was generated using the same software and platforms as in Experiment 1. For each fire pair, growth rates (α in the t^2 function) were selected to vary by the specified ratio difference. The time windows for each growth curve were selected to create control conditions to maximize the chance that participants would use growth rate to base their judgments. In the HRR max control, the maximum HRR displayed during the video clips was equated for each fire. For the HRR min control, the minimum HRR displayed during the video clips was equated for each fire. Based on perception research with visual acceleration [31], for the mean HRR control, the mean HRR during the video clip was equated. Stimuli videos were created using the same process as Experiment 1.

3.1.3. Procedure

The procedure was similar to Experiment 1, with the exception of the comparison instructions. Participants were instructed to select which fire was growing faster in the video. Instructions emphasized that growing fires give off more heat and become more intense with time; faster-growing fires do so in a shorter amount of time than slower-growing fires. Similar to Experiment 1, the participants completed practice trials and were provided with feedback regarding the accuracy of their responses during test trials.

3.1.4. Design

Similar to Experiment 1, the ratio difference in growth rate (calculated by dividing the larger alpha coefficient by the smaller one) was varied from small to large (within-subjects). The ratios used were extended from Experiment 1 to include 6.00 and 8.00 due to pilot testing indicating that performance was lower for growth rate ratios (six trials per ratio). Participants were assigned to complete either the fixed or varied footprint conditions (between subjects). The performance and qualitative coding measures were the same as Experiment 1.

3.2. Results

3.2.1. Performance

Binomial tests indicated that the performance was significantly above chance for a subset of ratios in the varied footprint condition (1.20, 1.50, 2.00, 4.00, 6.00, and 8.00, with *p*s < 0.01; for all other ratio comparisons, including the fixed footprint condition, *p*s > 0.1; see the Supplementary Material). A mixed model logistic regression predicting the correct response (random intercept for the participant) yielded significant main effects of ratio (scaled and centered), coefficient = 0.34, (SE = 0.06), z = 5.58, p < 0.001, OR = 1.40, footprint (varied as baseline), coefficient = 0.53, (SE = 0.12), z = 4.60, p < 0.001, OR = 0.59, and a significant interaction, coefficient = 0.29, (SE = 0.08), z = 3.52, p < 0.001, OR = 0.75 (intercept: coefficient = 0.68, SE = 0.08, z = 8.10, p < 0.001). Performance was significantly higher for larger ratios and varied compared to the fixed footprint condition, with the interaction being driven by similar performance results across conditions with smaller ratios (Figure 4).

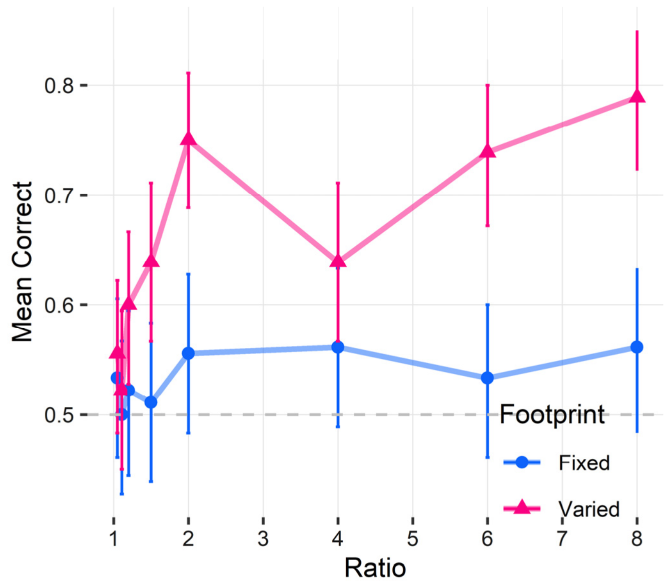

Figure 4. Mean proportion of correct responses in the comparison task for Experiment 2 for each ratio (larger growth rate divided by smaller growth rate) and footprint condition. Error bars indicate 95% confidence intervals.

3.2.2. Weber Fraction

A Mann–Whitney test indicated greater precision for the varied (M = 1.3, SD = 0.96, nearest fraction = 23/10), than for the fixed footprint conditions (M = 2.24, SD = 0.75, nearest fraction = 81/25), W = 691, p < 0.001.

3.2.3. Qualitative Analysis

A total of 53 participants (N = 26 for the fixed footprint condition; N = 27 for the varied footprint condition) provided text responses about the use of fire characteristics during the task (Figure 5). Significantly more than a single category was identified in the participant responses in both the footprint conditions for cue type (fire, flame, or smoke; one-sample Wilcox test; fixed, V = 88, $p = 0.038$; varied, V = 51, $p = 0.049$) and dimension (size, height, width, color, or puffing; fixed, V = 96, $p = 0.017$; varied, V = 71.5, $p = 0.025$). The same models as Experiment 1 were used to analyze how frequently characteristics were present in the participant comments. For cue type, a significant main effect of cue type was observed, χ^2 (2) = 7.90, $p = 0.019$ (for all others, *p*s > 0.7; see the Supplementary Material for descriptive statistics), with post hoc tests indicating that it was driven by comments mentioning fire more often than flames and smoke (adj. *p*s < 0.05). For dimension, a significant interaction with footprint was observed, χ^2 (4) = 11.43, $p = 0.022$ (main effect of dimension, $p < 0.001$; main effect of footprint $p = 0.862$; see the Supplementary Material for descriptive statistics). Post hoc tests indicated that the interaction was driven by comments mentioning height more often than puffing and color in the fixed condition and size more often than puffing in the varied condition (adj. *p*s < 0.05).

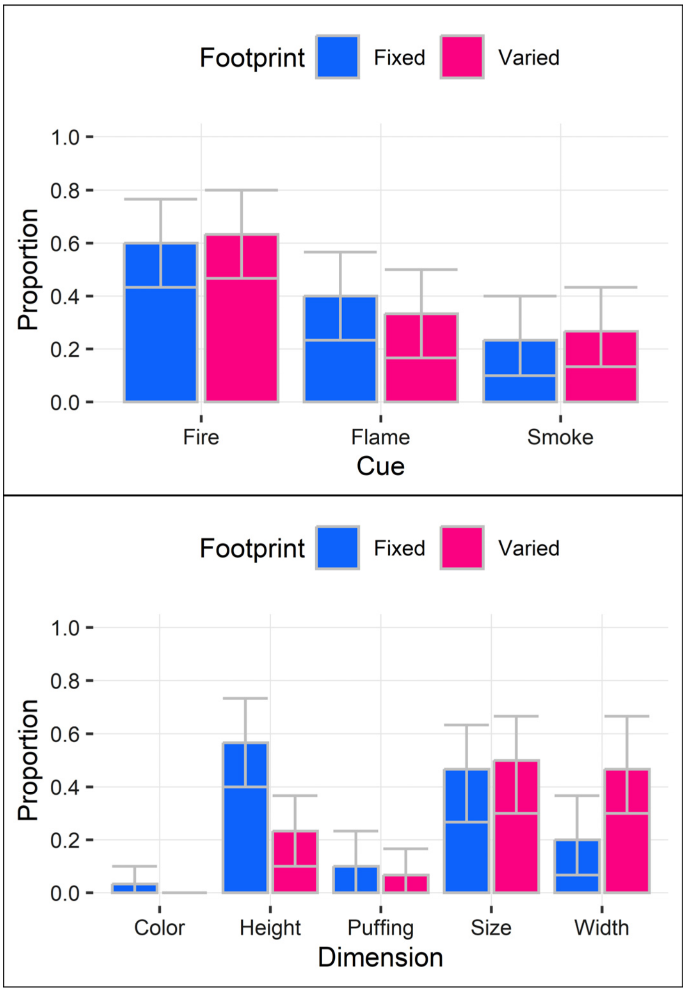

Figure 5. The proportion of participants whose comments contained each category of cue type (top panel) and dimension (bottom panel) by footprint condition in Experiment 2. Error bars indicate 95% confidence intervals.

Summary: Similar to Experiment 1, the responses indicated that the participants attended to multiple visual characteristics and the corresponding dimensions when comparing growth rates. General comments about the size of the fire were more frequently made in both conditions.

3.3. Discussion

To investigate how precisely the individuals could detect differences in growth rates, Experiment 2 presented participants with simulations of developing fires. The results indicated that participants could detect differences in fires that grew in footprint, but they required large ratios to do so. For fixed footprint fires that only increased in height, comparison performance was poor, with the Weber fraction estimates indicating that participants needed twice the ratio to reliably detect differences when compared to the varied footprint condition. Similar to Experiment 1, the participant responses indicated that they relied upon multiple dimensions of the fire to make their judgments. Overall, the results of Experiment 2 indicate that individuals are less precise when perceiving differences in the fire growth rate when compared to stable fire intensity.

4. Experiment 3

In a follow-up experiment, we investigated whether non-linear growth contributed to poor precision when comparing developing fixed footprint fires in Experiment 2. In the varied footprint condition, the fire intensity was visually indicated by vertical and horizontal spreading. In contrast, fires in the fixed condition did not spread horizontally. Furthermore, while the varied footprint condition did follow a t^2 growth curve in the HRR, the horizontal spread occurred in a linear manner. In contrast, the non-linear increase in the HRR for the fixed footprint fires could only occur vertically. In Experiment 3, we examined whether using a linear growth curve for the fixed footprint condition, such as the linear increase in width for the varied footprint condition, would lead to greater precision in comparison performance. However, linear growth is not a realistic curve for developing fires; Experiment 3 was intended to determine whether the distinction between linear and non-linear curves could account for the differences in judgment precision. We hypothesized that participants would reliably perceive differences in the rates of growth of fixed footprint fires that followed a linear function.

4.1. Methods

4.1.1. Participants

A new sample of 30 participants was recruited from the online participant panel Prolific and completed the study, hosted online via the Qualtrics XM platform. Participants varied in age (*M* = 39.70, *SD* = 13.04, *Min* = 20, *Max* = 67), biological sex (*N* Female = 16, *N* Male = 14), and race (*N* White = 23, *N* Black or African American = 5, *N* Asian = 2). A total of one participant reported having fire-related professional experience, and 21 participants reported experiencing at least one adverse fire event. For completing the study, participants were provided with a 5 USD monetary incentive (taking approximately 25 min to complete the study).

4.1.2. Materials

A new set of videos, displaying pairs of fires, was generated using the same software and platforms as prior experiments. For each fire pair, linear growth rates (slopes) were selected to vary according to the specified ratio difference. Similar to Experiment 2, the time windows for each growth curve were selected to create control conditions for intensity: HRR max, HRR min, and HRR mean. Stimuli videos were created using the same process as prior experiments.

4.1.3. Procedure

The procedure was the same as in Experiment 2.

4.1.4. Design

Similar to Experiment 2, the ratio difference in growth rate (calculated by dividing the larger slope coefficient by the smaller one) was varied from small to large (same ratios as Experiment 2; within subjects; six trials per ratio). Performance and qualitative coding measures were the same as prior experiments.

4.2. Results

4.2.1. Performance

Binomial tests indicated that the performance was significantly above chance for a subset of ratios (1.50, 2.00, 4.00, 6.00, and 8.00; *p*s < 0.01; for all the others, *p*s > 0.1; see the Supplementary Material). A mixed model logistic regression predicting the correct response (the random intercept for the participant) yielded a significant main effect of ratio (scaled and centered), coefficient = 0.67, (*SE* = 0.07), *z* = 9.97, *p* < 0.001, *OR* = 1.96 (intercept: coefficient = 0.61, *SE* = 0.07, *z* = 8.58, *p* < 0.001). Performance was significantly higher for larger ratios (Figure 6).

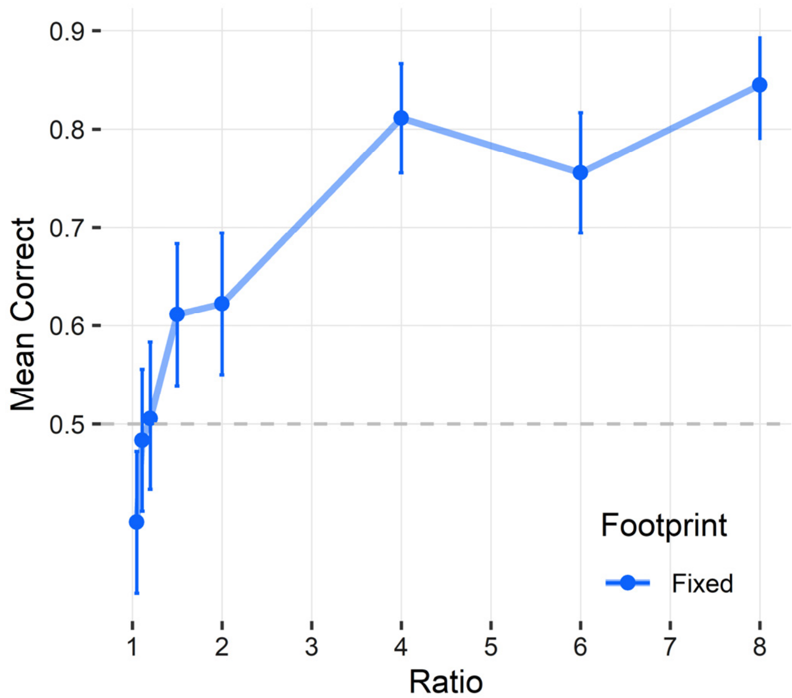

Figure 6. Mean proportion of correct responses in the comparison task for Experiment 3 for each ratio (larger growth rate divided by smaller growth rate). Error bars indicate 95% confidence intervals.

4.2.2. Weber Fraction

For a comparison with the previous experiments, the descriptive statistics for the Weber fractions were as follows: *M* = 1.02, *SD* = 0.65, and nearest fraction = 101/50.

4.2.3. Qualitative Analysis

All the participants provided text responses about the use of fire characteristics during the task (Figure 7). Significantly more than a single category was identified in the participant responses for cue type (fire, flame, or smoke; one-sample Wilcox test; V = 21, *p* = 0.013), and dimension (size, height, width, color, or puffing; V = 66, *p* = 0.001). Using similar models as in Experiment 2 that did not include the footprint condition as a factor, significant main effects of cue type, χ^2 (2) = 15.86, *p* < 0.001, and dimension, χ^2 (4) = 42.08, *p* < 0.001, were observed (see the Supplementary Material for descriptive statistics). Post hoc tests indicated that the main effect of the cue type was driven by comments mentioning fire more often than smoke and flames (adj. *p*s < 0.05). For dimension, the comments mentioned height more often than puffing or color, as well as width and size more often than color, width, or puffing (adj. *p*s < 0.05).

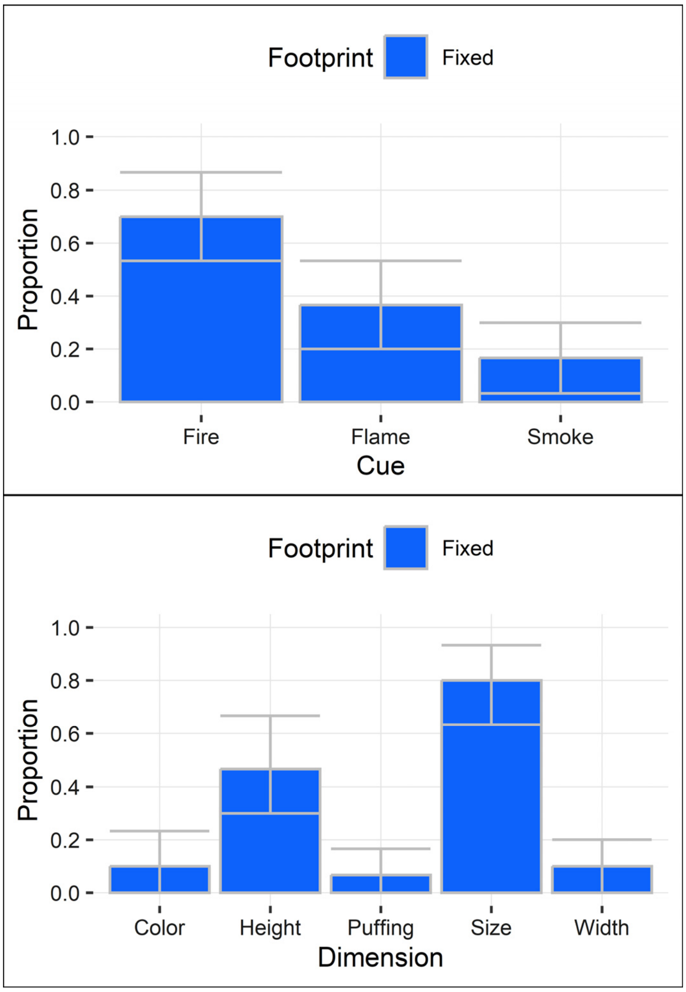

Figure 7. The proportion of participants whose comments contained each category of cue type (top panel) and dimension (bottom panel) in Experiment 3. Error bars indicate 95% confidence intervals.

Summary. As with the fixed footprint condition in Experiment 2, responses indicated that participants attended to multiple visual characteristics and their corresponding dimensions. Comments about the fire and the size, as well as height of the cues, were made most frequently.

4.3. Discussion

When provided with developing fires of a fixed width, the participants were able to perceive the differences when the intensity increased following a linear curve. In contrast to Experiment 2, the participants had higher performance when comparing the growth rates of the fires in Experiment 3, which grew linearly. This suggests that participants can use visual indicators of growth to judge which fire is growing faster when those cues increase linearly compared to non-linearly.

5. Cross-Experiment Weber Fraction Comparison

To examine how the types of fire intensity changes affected the performance, comparisons were made across experiments.

A Kruskal–Wallis test with a main effect of the experiment condition (Experiment 1—fixed footprint, Experiment 1—varied footprint, Experiment 2—fixed footprint, Experiment 2—varied footprint, and Experiment 3—fixed footprint) was significant, χ^2 (4) = 120, $p < 0.001$ (Figure 8). Post hoc contrasts (Benjamini–Hochberg-adjusted) indicated that the w fractions were the smallest for both of the Experiment 1 conditions (adj. ps < 0.001), with smaller fractions for the Experiment 1 varied condition versus the fixed footprint condition, (adj. p <0.001) and the largest fractions for the Experiment 2 fixed footprint conditions (adj. ps < 0.001); the fractions did not significantly differ for the Experiment 2 varied footprint conditions and for the Experiment 3 fixed footprint conditions (adj. p = 0.665; see the Supplementary Material).

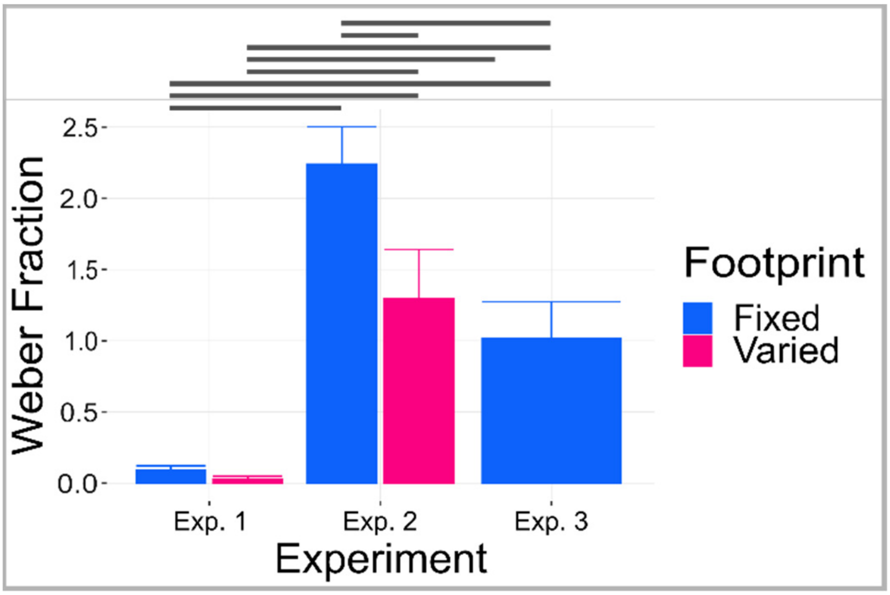

Figure 8. Weber fractions (w) across experiments and footprint conditions. Smaller w values indicate greater precision. Error bars indicate 95% confidence intervals. Annotated bars indicate significant comparisons after adjusting for family-wise error (adj. ps < 0.001).

6. General Discussion

The goal of the present study was to examine how precisely individuals could perceive the intensity and growth rates of fires. Across three experiments, participants compared two visually simulated fires and reported the characteristics they used to judge which was greater in intensity or growth. Participants could distinguish between the smallest differences when judging fire intensity, whereas they required larger differences to reliably compare fire growth rates. Across all of the experiments, participants reported using multiple fire characteristics to make their decisions, most frequently mentioning the dimensions of the fires (more generally), as well as the flames and smoke. These results indicate that, similar to other non-symbolic quantities, fire intensity can be precisely perceived visually by using multiple visual cues.

6.1. Precision of Fire Intensity Perception

Individuals were able to precisely detect differences in the intensity of fires. In both footprint conditions, reliable ratio effects were observed with higher accuracy when the differences in the fire intensity were greater compared to when they were smaller. In addition, compared to previous non-symbolic quantity research, the observed Weber fractions for the intensity comparisons were similar to judgments of individual size and length and were smaller than those of set-size quantities of number and density [18]. This suggests that humans are capable of perceiving differences in dynamic quantities with multiple visual indicators, such as fire intensity, at a similar level as for static spatial quantities. For intensity, this may be due to the participants being able to have multiple redundant cues indicating which fire was larger. This is supported by the participant self-reports, which indicated that they did indeed attend to multiple characteristics, particularly the height of the flames, when making ordinal judgments.

Higher precision was observed when comparing the intensity of fires that had varied versus fixed footprints. This suggests that the added cue of footprint width improved fire intensity perception. Self-report results support this conclusion, with the height of the fire more frequently mentioned by participants than the width in the fixed footprint condition; this suggests that it was relied upon less in the varied footprint condition. Improvements in performance with multiple cues have also been observed with non-symbolic quantity judgments. For example, better w values have been observed when participants judged which of two arrays of dots was greater in value when the numerically greater arrays contained dots that were also larger in size [32]. For the fire comparisons, observers incorporated multiple visual cues of intensity and were more precise when attending to the footprint size.

6.2. Impact of Growth on Fire Precision

The present study suggests that observers are inaccurate when judging how quickly fires are increasing in intensity. For fixed footprint fires, participants were imprecise when comparing t^2 growth rates in Experiment 2 despite reporting that they attended to the height of the fire. The Weber fractions were more precise in Experiment 3 when fixed footprint fires increased in intensity at a linear rate. This indicates that participants were more sensitive to differences in the speed at which the fire was increasing when compared to the acceleration of fire intensity. Evidence from the varied footprint condition aligns with this finding. Although the overall intensity of fires accelerated via a t^2 growth rate in Experiment 2, the size of the fire footprint increased at a linear rate. Similar w scores for the varied footprint in this experiment and the fixed footprint in Experiment 3 indicate that participants were likely attending to the linear increase in footprint width rather than acceleration rate in intensity. Indeed, the greater precision when judging fire intensity when footprint width covaried aligns with participants focusing on width growth rates. These results indicate that observers were more likely to attend to linear, over non-linear, visual cues when judging fire growth rates.

The fire growth rate precision in the present study aligns with prior research investigating the perception of visual acceleration. Individuals were worse, in past studies, when judging the acceleration of dots moving across a screen compared to judging the velocity [19,33]. Furthermore, individuals may not rely on the acceleration information when making such judgments and instead compare the velocity at the start and end of an animation [34]. For the present study, the observation of worse w values for the fixed footprint condition for the t^2 compared to the linear growth rates is in line with these findings. Although observers can detect visual acceleration, models of behavior and neuro-imaging data suggest that the internal representations of acceleration are noisy [35] and that the salience of visual movement information decreases when transforming from velocity to acceleration [33]. Overall, this indicates that the kinematic characteristics of the visual cues of fire intensity may share underlying processes with visual object perception.

6.3. Implications for Models of Occupant Behavior

The results of the present study indicate that the visual characteristics of fires can be used to estimate changes in their intensities. These play an important role in the models of human behavior during fire events. In the PADM, occupants in the initial phase have to detect cues that indicate a fire emergency is present in order to engage in decision making during subsequent phases [4]. Indeed, the visual cues of fires, including flames and smoke, have been reported as characteristics that occupants can use to gauge the severity of a fire [2]. The present study provides estimates of how precisely humans can use visual fire cues to mentally represent the intensity of fires. When given 8 s of observation, humans can detect small differences in fire intensity that are on par with comparing the sizes of two objects. However, observers were much worse at representing the growth of fires when using visual cues. This is in line with prior research that observed poor performance when estimating how long it took fires to reach a specific intensity [12]. When judging growth rates, the present study indicates that observers are likely to attend to the visual characteristics of fires that change in a linear manner. This means that occupants are less likely to be able to detect changes in fire cues for fixed footprint fires. Overall, the present study provides evidence that occupants can detect differences in fire intensity by using visual cues, but are better able to do so with growth rates for fires that spread by increasing in footprint area.

Individual differences in fire intensity precision were observed in the present study. Similar to non-symbolic quantity perception [7], participants varied in w values for both intensity and growth judgments. For models of occupant behavior, this means that some individuals will be worse at detecting changes in fire intensity than others. This can affect the predictions of the length of time before an occupant takes protective action. Some individuals will require larger differences in visual characteristics to notice changes in fire intensity, which may delay their responses when compared to other occupants. Accounting for individual differences in fire intensity perception will be crucial for accurate estimates of the RSET in performance-based models of occupant behaviors.

6.4. Limitations and Future Directions

Extensions of the present study can investigate how situational factors influence fire intensity perception. The present research used simulated fires that were devoid of environmental factors to estimate how precisely individuals could represent intensity. However, prior research has noted that the building environment can influence the occupant responses to fire events [4]. With simulation software capable of rendering different building environments, subsequent studies can compare fire intensity judgments across different types of rooms. In addition, the fires were placed within virtual environments that did not contain other objects, including those that could be used to estimate the dimensions of the room or fire. Without references to physical size, participants could have perceived the fires as either small or large. Future studies can include objects with familiar physical sizes to extend the findings of the present study. Although the fire dynamics in the present study were limited to well-specified simulations, fires vary in complexity and progression. Extending the approach used in the present experiments to fires that vary in fuel source, soot production, and stages in fire development can provide greater insight into how the perception of visual cues changes during the time course of fires. The present study used simulated fires to render multiple intensities and growth rates. Whether the levels of precision observed in the present study transfer to real fires remains to be determined. However, using real fires in the variety of conditions of the present study may not be feasible. Research using simulated fires in immersive virtual reality, paired with multisensory stimuli that include heat lamps and smoke odorants [36], offers a potential compromise. Studies that use multi-sensory, immersive virtual reality can further examine whether the perceptual performance observed in the present study extends to more realistic simulations.

Understanding how the perceptions of visual fire cues are connected to the judgments of risk is an immediate next step. Prior research indicates that occupants can use visual cues to judge the posed risk of a fire [2]. The present study provides evidence as to how precisely individuals can perceive fire cues; subsequent research can identify how changes in said cues influence risk perception. Furthermore, individual differences regarding fire precision were observed across experiments and conditions. Subsequent research can investigate what factors contribute to the variability in fire precision across individuals. For example, experience with and exposure to fire may account for individual differences. Although the design of the present study was not able to examine this connection, future studies that focus on fire precision within a specific set of conditions can investigate how experience with fire affects precision when estimating the fire intensity and growth rate.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire6090328/s1, Table S1: Binomial tests investigating whether participants selected the more intense fire for each ratio and direction condition compared to chance (0.50) for Experiment 1; Table S2: Descriptive statistics of comment category probabilities by footprint condition in Experiment 1; Table S3: Binomial tests investigating whether participants selected the faster growing fire for each ratio and direction condition compared to chance (0.50) for Experiment 2; Table S4: Descriptive statistics of comment category probabilities by footprint condition in Experiment 2; Table S5: Binomial tests investigating whether participants selected the faster growing fire for each ratio compared to chance (0.50) for Experiment 3; Table S6: Descriptive statistics of comment category probabilities in Experiment 3; Table S7: Post hoc non-parametric contrasts comparing Weber fractions across experiment conditions (*p*-values adjusted using Benjamini-Hochberg method).

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